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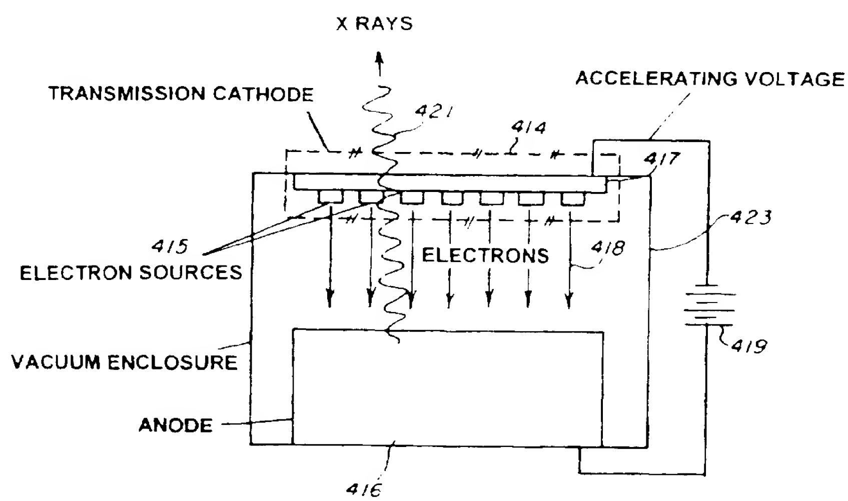
(54) Title: TRANSMISSION CATHODE FOR X-RAY PRODUCTION



(57) Abstract: The transmission cathode (414) for X-ray ... [illegible]

[illegible] ... non conductive mechanical structural components, preferably diamond, or silicon dioxide or boron carbide. The transmission ... [illegible]

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TRANSMISSION CATHODE FOR X RAY PRODUCTION

TECHNICAL FIELD

This device pertains generally to a device for generating X rays and more specifically to an X-ray transmission cathode wherein the X rays produced in an evacuated X-ray tube by an anode or sample are allowed to exit the tube through the cathode.

BACKGROUND ART

The typical configuration for a sealed X ray tube involves a resistively heated, drawn wire filament cathode for generating free electrons in vacuum, and a metallic anode held at high voltage with respect to the cathode. The emitted electrons are electrostatically accelerated to high energy and made to collide with the anode, which then emits the X rays. The voltages required for economical X-ray emission exceed the binding energy of inner electrons in the atoms of the anode, typically kilovolts. The anode emits continuum bremstrahlung X rays as well as characteristic X rays. Emission occurs in all directions, but the intensity in any direction is modified by the absorption of the X rays as they depart their points of origin. The characteristic rays are distinctive for each of the chemical elements, and form the basis of the well known elemental analysis by X-ray emission. Selective detection, processing, and display techniques have been used to record the characteristic rays and analyze the spatial variations of composition in X-ray emitting materials.

As used herein, an x ray photon is a photon with sufficient energy to ionize a neutral atom by photoelectric absorption. There is a wide variation in the energy range of ionizing photons.

The usual geometry for sealed X-ray tubes **10**, as shown in **Figure 1a**, includes a filament cathode **12**, an anode **14**, and a separate X-ray "window" **16** made of thin material, usually metal, through which the X rays **18** exit the vacuum sealed X-ray tube **10**.

window **16** is enhanced for smaller magnitudes of that fraction. The filament cathode **12** is connected between a pair of terminals **13** and **17**, to a cathode low voltage power supply **22** which supplies current to the cathode **12** to heat the filament cathode **12** and excite electron flow **15**. A high voltage power supply **24** is connected to the anode **14** to accelerate the flow of the emitted electrons **15.** In this design, the anode **14** placement and shape is subject to two major geometric constraints, (1) maintaining sufficient distance between the anode **14** and other items that the electric fields within the vacuum sealed X-ray tube **21** remain low enough to preclude breakdown and surface currents, and (2) insuring that the window **16** placement is such that X rays **18** are afforded sufficient solid angle to reach the outside of the vacuum sealed X-ray tube **21** with acceptable levels of absorption.

Typical vacuum sealed X-ray tube **10** design of the prior art places the sample or X-ray target **23** and window **16** such that X rays **18** are emitted at or near 90 degrees from the path of the incident electrons. Because X rays are less strongly absorbed than the electrons, angles are commonly chosen such that the electron penetration distance in the anode **14** is shorter than the exit path for emitted X rays **18**. X-ray **18** takeoff angles of 6 to 30 degrees (from the surface of the anode **14**) are not uncommon; appreciable X-ray absorption in the anode **14** occurs at these low angles.

A variant among tube designs of the prior art is the transmission anode, end window, tube **20**, as shown in **Figure 1b**, commonly known as the end-window tube , in which the transmission anode **26** functionalities of an anode and a window are combined in a single member. A transmission anode **26** must allow the electrons **29** to strike the anode **26** to produce X rays **31**, dissipate charge and heat from its surfaces and from throughout its volume, and permit the X rays **31** to pass through to the outside; these requirements are usually achieved with transmission anodes **26** made of thin metal foils. The transmission anode, end-window tube **20** is advantageous in some applications, but the requirement for a thin anode **26** results in lower X-ray **31** output power. It is quite common for the end-window anode **26**, an exterior component, to be held at ground potential, which leads to the requirement for the cathode **33** portion to be at high voltage. The cathode

filament current power supply **34** must float at high negative voltage while the anode **26** is connected to a tube high voltage power supply **32** to accelerate the flow of emitted electrons **31**.

In contrast to tube designs of the prior art shown in **Figures 1a** and **1b**, the transmission cathode, end-window, tube discussed below, enables the X rays **31** from the transmission cathode **33** to exit the anode **26** at the same angle that the electrons **29** are incident, thus reducing the X-ray absorption and enhancing tube **2** output and permitting grounded exterior components. The transmission cathode **33** is not bombarded by high energy electrons and need not dissipate as much charge or heat from within its volume, thus it need not be as good a volume conductor of either.

While the hot filament cathode based on thermionic emission is very common, alternative technologies based on field emission, photo emission, and plasma emission have been investigated as well. Field emission tips have been used for X-ray production in the past on radiography machines to produce nanosecond pulses of X rays by accelerating electrons from an array of emitters into a metal foil end-window anode. Photoemission involves irradiating the cathode with suitable light sources capable of stimulating the cathode to emit electrons. **SEE**, U.S. Patent No. 5,042,058, Rentzepis, issued August 20, 1991, entitled ULTRASHORT TIME-RESOLVED X-ray SOURCE. Plasma emission cathodes involve locally heating the cathode surface to temperatures sufficient to produce a plasma, from which electrons are emitted. **SEE**, U.S. Patent No.5,335,258, Whitlock, issued August 2, 1994, entitled SUBMICROSECOND, SYNCHRONIZABLE X-ray SOURCE.

Spatial resolution based on direct X-ray emission has been practiced with the electron microprobe and scanning electron microscope. Fluorescent X-ray emission has also been used for compositional mapping. **SEE**, U.S Patent No. 5,742,658, Tiffin et al., issued April 21, 1998, entitled APPARATUS AND METHOD FOR DETERMINING THE ELEMENTAL COMPOSITIONS AND RELATIVE LOCATIONS OF PARTICLES ON THE SURFACE OF A SEMICONDUCTOR WAFER.

[illegible]
and Cha [illegible] Tang ET AL., PLANAR LENSES FOR FIELD-EMITTER ARRAYS

J. Vac. Sci. Technol. B **13**(2), Mar/Apr 1995, pp. 571-575.

Due to the unavailability of lenses for X rays, geometric imaging means are commonly used to generate X-ray images. X radiography **30**, as shown in **Figure 1c**, in which a sample **42** is imaged with X- rays **38**, typically uses point projection imaging. A small ("point") source of X- rays **36** emits X- rays **38** spherically outward through the exit window of the tube (not shown). The sample **42** to be radiographed is placed between the X-ray source **36** and the imaging detector **44**, e.g., an X-ray film plate used for medical imaging. The spatial resolution of the image is limited by the size of the X-ray point source **36**. The achievable X-ray output power cannot exceed the ability of the X-ray tube **37** to absorb the heat load of its internal electron beam within the small focal point from which the X- rays **38** emanate. Where the sample is in close proximity to or contacting the imaging detector (typically X-ray film), the arrangement is called contact radiography and unit magnification is achieved. In typical applications where a magnified image is required, this can be obtained by moving the image plane further from the source and the image becomes a projection radiograph **45**. This, in turn, increases the X-ray flux required to achieve an exposure, and places greater demands on the X-ray tube (not shown) and power supply.

Areal X- ray sources are not widely used for imaging, as the common filament cathode X-ray tubes are most conducive to providing small X-ray sources.

X-ray windows must transmit X rays, maintain vacuum integrity as essential to the electron trajectories, and, if needed, allow for the dissipation of charge or heat. The cathodes taught in the prior art do not satisfy these requirements and are insufficiently transmissive to X rays to permit their use as an X-ray window.

DISCLOSURE OF INVENTION

The objective of this invention is to provide a device for X-ray production wherein the X rays are transmitted out of the device through the cathode.

Another objective of the invention is to provide an areal X-ray source for X-ray fluorescence (XRF) system applications.

Another objective of the invention is to provide an areal X-ray source for X-ray emission analysis applications.

Another objective of the invention is to provide an areal cathode with addressable elements in an X-ray source for use with a compositionally structured anode for the generation of tailored X-ray spectra.

Another objective of this invention is to provide an areal X-ray source for use with compositionally structured samples, for use as an electron probe system.

Another objective of the invention is to provide an areal X-ray source for use with compositionally structured samples, for use with a collimator as an imaging electron probe system.

Another objective of the invention is to provide a cathode with addressable elements in an X-ray source for use with compositionally structured samples, for use as a imaging electron probe system.

Another objective of the invention is to provide a cathode with addressable elements for use with topographically or compositionally structured samples, for use as an scanning electron imaging system.

Another objective of the invention is to provide an areal X-ray source for use with a collimator for radiography applications.

These and other objectives are achieved by the use of a transmission cathode in an device for generating X rays. In the device an electrical current generated by a low voltage power supply produces an electron flow from the transmission cathode that is accelerated by a high voltage and propagates to an anode. As the X rays are emitted, a primary X-ray beam passes through the cathode striking a sample placed outside the tube. The transmission cathode is comprised of an electron emitter structure, preferably, a electron field emitter diode or thermionic emitter or a photoemitter or a nanotube or a pyroemitter or a piezoemitter, fabricated, preferably of elements of atomic numbers of 14 (silicon) or below, with electrically

n nonconductive mechanical structural components, preferably,

diamond or silicon dioxide or boron carbide.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1a shows a sealed, evacuated X-ray tube typical of the prior art.

Figure 1b shows an end-window, transmission *anode* tube typical of the prior art.

Figure 1c shows x radiography using point projection imaging with a point source X-ray tube, typical of the prior art.

Figure 2a shows a sealed, evacuated X-ray transmission cathode device as described in the preferred embodiment.

Figure 2b shows a cross sectional view of a transmission cathode.

Figure 2c shows a cross section of another transmission cathode.

Figure 2d shows the threshold voltage for a gatable diamond electron field emitter of the transmission cathode.

Figure 2e shows one manner in which the addressing of a selected row of gatable electron sources within an array of electron sources may be accomplished.

Figure 2f illustrates one manner in which the addressing of individual gatable electron sources within an array of electron sources may be accomplished.

Figure 3 shows a simple X-ray tube with an anode and a simple transmission cathode operating with an acceleration voltage.

Figure 4 shows components of a sealed, evacuated X-ray transmission cathode device with an array of cathode electron emitters, current supply, and accelerating voltage.

Figure 5a shows components of an evacuated X-ray transmission cathode device with circuitry to enable the electron source array to be gated and addressed in groups of electron emitters, and with a compositionally structural anode for producing tailored X-ray spectra, with particular application to X-ray fluorescence analysis.

Figure 5b shows a transmission cathode X-ray tube in use as a source of primary X- rays in an X-ray fluorescence system.

Figure 5c shows a transmission cathode X-ray tube in use as a source of primary X- rays in an X-ray fluorescence system in

which the source and detector are designed for compact configuration. The transmission cathode X-ray tube is made in an annular shape, with the detector located on the axis of the annulus.

Figure 6a shows a miniature electron microprobe with a cathode as described in the preferred embodiment with array of gatable electron emission sources that are individually addressable and may be scanned. Operation of the cathode in two-dimensional scanning mode allows a non-imaging X-ray detector system to record the sample spectrum at each illuminated point, and process the data as a two-dimensional scan to record the hyperspectral X-ray image of the sample.

Figure 6b shows deflection plates used to enhance imaging resolution, provide redundancy, and add control over beamlet impact point.

Figure 6c shows an imaging electron probe emission analysis system in which the sample is placed at the anode position of a transmission cathode X-ray tube, with image formed by an imaging X-ray optic such as a collimator, and detection of the X rays emitted by the sample being performed by an external imaging detector viewing the sample through the transmission cathode. The imaging detector records an image of the X-ray emission from the sample. Use of a spectral imaging detector allows the recording of the hyperspectral X-ray image of the sample.

Figure 6d shows an electron probe emission analysis system with an anode-window, through which electrons from the transmission cathode are accelerated to impact a sample located outside the sealed tube. X- rays emitted by the sample are transmitted by the anode-window and by the transmission cathode and detected by an X-ray detector. Scanning the transmission cathode enables compositional imaging of the sample. X-ray emission may be detected from the front of any sample, or through samples that are sufficiently thin to transmit their own emitted X- rays.

Figure 7 shows an X-ray probe emission analysis system, in

emission from the sample may be used to image the sample.

Figure 8a shows a compact collimator X-radiography system with a large area, transmission cathode X-ray source. The collimator is disposed between the source and the sample, thus reducing the amount of x rays irradiating the sample.

Figure 8b shows a compact collimator X-radiography system with a large area, transmission cathode X-ray source. The collimator is disposed between the sample and the imaging detector.

Figure 9a shows a miniature scanning electron imaging system in which the sample is placed at the anode position of a tube having an addressable cathode array of gatable electron emitters. As each emitter is addressed in turn, scattered and other electrons originating from the sample or anode are collected by the unaddressed gate electrodes and recorded to form an image of the sample and anode. Alternatively, the sample current may be collected and imaged in a similar fashion. Two-dimensional scanning is accomplished by addressing the cathode, and collimation is provided to the beamlets by electrodes on the cathode.

Figure 9b shows a cross section of a miniature scanning electron imager.

Figure 10 shows a cross section of a miniature scanning electron imager with optional elements for controlling beam profile or beam deflection, or for retarding electrons emitted by sample or anode.

Figure 11 shows a variant construction for a diamond field emitter.

Figure 12 shows a transmission cathode X-ray tube, monochromatic X rays from which are emitted in a beam of altered cross section by means of an asymmetrically diffracting X-ray optical element.

BEST MODE FOR CARRYING OUT THE INVENTION

In the preferred embodiment of the transmission cathode tube **30**, as shown in **Figure 2a**, an X-ray transmission cathode **46** is so designed that X- rays **48** produced within an evacuated, sealed X-ray tube **52** or pumped tube, are allowed to exit the tube **52** through the cathode **46**. The X-ray transmission cathode **46** emits electrons supplied by a low voltage power supply **54**. Electrons **56**

emitted by the transmission cathode **46** are accelerated by high voltage applied by a high voltage power supply **58** and impact the anode **62** to produce X- rays. The X- rays are emitted in all directions from the point of impact. X- rays **48** that strike the tube wall **52** are heavily absorbed. X- rays **48** that strike the transmission cathode **46** are transmitted and thus are emitted outside the tube **52**.

Typical uses of an X-ray tube with transmission cathode **46** includes X-ray fluorescence (XRF) analysis, X-ray emission analysis, X-radiography (i.e., X-ray imaging), and X-ray diffraction. Further use of the scanning cathode array is found in the area of electron imaging systems.

A technologically simple configuration of known elements, combined to achieve a similar tube geometry, involves a free standing thermionic emission filament cathode disposed between an X-ray window and an anode. This device is distinct from all transmission cathode devices taught herein, in that the cathode (electron source) and window functionalities are not coalesced into a single item. The thermionic filament, which is operated at high temperature in proximity to the window, would quickly contaminate the window with evaporant and reduce its X-ray transmissivity. The filament cathode would produce a shadow image in the emitted X rays, which would be of concern, for example, if it produced image contrast and fell within the imaging field of a radiographic system or monochromatic beam used for diffraction. The free standing filament cathode does not achieve the respective advantages taught below for transmission cathodes. The filament cathode is not an areal cathode, and does not achieve the respective advantages taught below for transmission cathodes. In addition, the free standing filament cathode is not addressable, gatable, or scannable, and does not achieve these respective advantages taught below for transmission cathodes.

Referring to **Figure 2b**, the transmission cathode **46** is comprised of an electron emitter **64** structure, preferably, a film forming a diamond field emitter **66**, vapor deposited on a pre-

silicon. **SEE**, Kang et al., "SUBVOLT TURN-ON VOLTAGE SELF-ALIGN GATE DIAMOND EMITTER FABRICATED BY SELF-ALIGN-GATE-SHARPENED MOLDING TECHNIQUE", J. Vac. Sci. Technol. B, vol. 17 no. 2, Mar/Apr 1999, p. 740-3. The diamond film **66** is intentionally deposited with a small component of sp^2 chemical bonding content. The silicon **72** mold is partially etched away to reveal the diamond emitter tips **74**. The heavily doped silicon mold **72** is used as the positive electrode of the electron emitter, that is, applying a positive potential to the silicon **72** with respect to the diamond **66** results in electron emission by the diamond tips **74** into the space above the openings in the positive electrode. The diamond field emitter **66** may be fabricated to a thickness and geometry to provide its own support, in which case an additional structural holder **64** is not required. However, other elements, including metal conducting layers, doping layers, and other electron emitter designs may be used in variant electron emission designs, provided as they meet the criterion of being transmissive to X rays. **Figure 2c** illustrates a novel transmission cathode **40** with a metal layer forming the positive electrode **402** of the electron emitter **404** .

Electron emitters of many types, including field emitters, release electrons with a low energy per electron. This is illustrated in **Figure 2d**, in which the threshold for emission by diamond field emitters is presented. Diamond field emitters without a surface treatment **74** are seen to require a higher value of voltage per micrometer (and therefore a higher threshold voltage) than do diamond field emitters that have undergone a surface treatment **76**. The surface treated diamond field emitters **76** have a desirably low threshold voltage. The low voltage at which electrons are emitted by diamond field emitters and other electron emitters allows the individual emitter to be gated on or off by application of a suitable voltage to a gate electrode.

Referring again to **Figure 2c**, an above-threshold voltage may be applied to all emitters **404** simultaneously causing them all to emit. By selectively applying an above-threshold voltage to certain emitters **404** and not others, the chosen emitters **404** may be induced to emit while the others do not emit. For example, in **Figure 2e** is shown an arrangement of gate electrodes **406** that permits a selected row of emitters **408** within the array of

emitters **100** to be addressed and gated ON. A voltage, exceeding the threshold voltage, is applied to the selected row **408** and emitters **412** within that row **408** will emit electrons. Other arrangements or groupings of emitters **406** may be designed to be selectable, for example by hard wiring the gate electrodes into arrangements or groupings or by controllably switching interconnections between gate electrodes **406**.

For the emitters **40**, as shown in **Figure 2d**, the change from nonemitting to emitting conditions occurs abruptly. For an applied gate voltage of half the threshold voltage, electron emission remains suppressed. In **Figure 2f** is shown an arrangement of gate electrodes **78** that permits individual emitters **82** to be addressed and gated on. Two gate electrodes **78** are disposed above each addressable emitter **82**. The gate electrodes **78** may be electrically connected in rows **84** and columns **86**, as depicted in **Figure 2f**. The rows **84** are separated from one another laterally by an insulating surface **92**, and the columns **86** are separated from one another laterally by another insulating surface **88** which is depicted for convenience in illustration to be also the transmission cathode substrate **88**. A sub-threshold voltage **85**, less than the threshold voltage, is applied to each of the two gate electrodes **78** disposed above the desired emitter **82**. The desired emitter **82** experiences a net voltage at or above the threshold, and emits a beamlet of electrons. The gate electrodes **78** of adjacent emitters **82** may also receive a voltage, but only one gate electrode**78** will experience a voltage at any emitter **82** other than the desired emitter, and thus only the desired emitter will exceed threshold. (Other geometric arrangements of a plurality of gate electrodes may be applied at each emitter **82**, for example, three electrodes **78**, with the adjacent electrodes **82** being electrically connected in lines at 60 degree angles instead lines at 90 degree angles. Other addressing means may be employed, such as individually wired gates addressed by switching circuitry. Collimation and focusing of the beamlets may be achieved by suitably shaping the gate electrodes or by addition

voltage provides a means for controlling the magnitude of the current. Thus, gating includes the capacity to exercise such control.

Features on the microfabricated cathodes **40** may be made of any suitable material, as dictated by the functionality required. For example, aluminum or other metal conducting paths or layers are admissible. The physical thickness of such conducting paths is very small, and the resultant X-ray absorption in them is not great locally, and even lower when averaged over the entire area of the cathode **40**. Thus enhanced functionality can be acquired by adding structures of higher atomic number, while retaining a usefully low value of X-ray transmission through the full aperture of the transmission cathode **40**.

There is a wide range of techniques for treating surfaces, processing materials, and fabricating structures, operating on length scales from the nanometer scale to the macro scale, which may be applied to the transmission cathode tube **40** or its components. These are well known to those skilled in the art.

The transmission cathode substrate **88** or window material may be any X-ray transmissive material satisfying the criteria set forth herein and durable to X-ray irradiation, such as thin metal, polyimide, nitrides, carbides, diamond, or silicon. Particular advantages may be achieved with substrates made of elements in the low atomic number range of 1 and 14 (hydrogen through silicon), due to the lower X-ray absorption, per atom, of low atomic number elements, and the fact that their absorption edges fall well below the energies used in most practical X-ray work.

Many advantages are inherent in the use of electron emitters having closely placed electrodes to perform the functions of electron extraction or gating. One of these advantages is the low voltages which may be applied to achieve the extraction or gating functions, a particularly important issue for devices controlled by solid state electronics. However, in X-ray applications for which high voltages are required to stimulate x ray production, it is not always required to employ low voltages or to incorporate these closely placed electrodes in order to achieve X-ray emission. **Figure 3** illustrates a fundamental X-ray tube configuration of a simple transmission cathode **414** and an anode

416, held in an environment suitable for electron **418** transit between the cathode **414** and anode **418**. The transmission cathode **414** may be, for example, all diamond on which diamond emitter tips **415**, or other types of electron sources, are formed as before but without overlays to form extraction or gate electrodes. Or, emitter tips **415**, formed of any material that performs as an emitter, may be placed on an electrically conductive, X-ray transmissive substrate **414**, and occupying a fraction of the total area of that substrate. The emitter tips **415** may be made of the same material as the substrate **417**, if that material performs as an emitter. This combination of emitter tips **415** and substrate **417** forms a transmission cathode **414**. For sufficiently close spacings between emitter tips **415** and anode **416**, the application of high voltage between the cathode**414** and anode**416** is sufficient to enable electron emission. Emission current may be gated by removing either the high voltage or the current supply. Emitted electrons **418** are accelerated to the anode **416**, where they produce x rays **421**. Emitted x rays **421** may transmit through the transmission cathode **414** and escape the X-ray tube **423**.

In further detail of the cathode and anode arrangement of the preferred embodiment of the transmission cathode tube **50** , as shown in **Figure 4**, an X-ray transmission cathode **92** with electron emitter array **94** is so designed that X rays **96** produced within an evacuated sealed X-ray tube, or pumped tube (not shown), are allowed to exit the tube (not shown) through the cathode **92**.

An electrical current generated by a low voltage power supply **104** produces an electron flow **106** from the transmission cathode **92** that propagates to the anode **108** which is impacted by an array of overlapping beamlets at beamlet impact locations **114**. As electrons **106** strike the anode **108** X rays **96** are generated that pass through the cathode **92** and exit the tube (not shown).

The electron flow **106** from an individual electron emitter or an array of individual electron emitters **94** on the cathode is accelerated towards the anode **108** by a high voltage from a power

The transmission cathode **92** may use a thermionic, field, photo, pyroelectrically stimulated, piezoelectrically stimulated, or plasma emission to generate the electron current within the tube (not shown). In order to qualify as a transmission cathode **50**, the X rays **96** need only to be able to exit through the cathode **92** in sufficient quantity to be of use. The transmission cathode **50** may include features covering a part of its area which heavily absorb X rays, so long as the transmission through the remaining cathode **92** area remains sufficient to be useful. Features on or in the cathode **50** may be fabricated of material of any atomic number or combination thereof. The cathode **50** may also include surface coatings, for example to provide a conducting path to drain away surface charge, or dopings, for example to control bulk conductivity.

Unlike the end-window tube, the transmission cathode **50** may be used with a thick anode **108**, which improves X-ray **96** production efficiency compared to thin anode X-ray production. The near normal angles of X-ray emission **96** attainable from transmission cathodes **50** offer less absorption than is typically experienced with thick target, side window geometries having the common non-transmission cathode. The transmission cathode **50** may be held at ground potential which simplifies the electronics (not shown) required to supply current and acceleration potentials to the cathode **50**. As the transmission cathode **50** is a component of the tube (not shown) externals, it is desirable from a safety standpoint for it to be at ground potential.

In another preferred embodiment **60**, as shown in **Figure 5a**, for producing tailored, variable X-ray spectra, the transmission cathode **116** in the device **60** is defined in regions of electron sources **117**, each of which may be gated ON or OFF. Each cathode region **117** impacts a different respective anode region **118**. For convenience in illustration, the regions **117** and **118** are shown as rectangles, although other shapes may also be used. The compositions of the anode regions **118** are variously fabricated to deliver differing X-ray spectra. This device is capable of irradiating a sample **122** with X rays **124** of varying wavelengths.

As the energy of emitted electrons **128** is initially low in thermionic, field emitters and photo emitters, individual electron sources of these types in the emission arrays **118** may be

electrostatically gated by using low voltage **126** gating near the electron source; only those sources that are gated on will produce electron beamlets which pass into the region of the tube where the electrons will be accelerated to high voltage and produce x rays. The individual electron sources **117** of the array may be made to be switched ON or OFF, or to emit a variable value of current, as discussed above, in relation to field emitter electron sources. The low extraction voltages **126** allow control by control circuitry **136**, and thus enable the electron array source in the transmission cathode **116** to be addressed and scanned; the X-ray emission **125** from the electron target can thus be scanned under control of circuits **136**. Methods and techniques of vacuum microelectronics have been published by others for use in electron devices. Here is taught their use for X-ray production and X-ray imaging.

Plasma electron sources are capable of emitting much more energetic electrons, depending on the plasma conditions. Gating of plasma emitters will require gating voltages commensurate with the energy of the emitted electrons. The degree of cathode mass erosion to which plasma sources are susceptible is a disadvantage not shared by the other methods, and limits the practical uses of plasma emission sources.

An areal cathode **116** with multiple areas of gatable electron emission sources **118** and respective anode compositions will be useful for spectrographic applications such as X-ray fluorescence analysis.

A low-voltage power supply **126** applies a voltage to the cathode **116**, as described above, generating an electron beam or flow **128** that is accelerated by high voltage **132** to an anode **134**. The anode **134** is specifically fabricated with different known compositions at different known locations. The anode **134** is comprised of various known segregated elements **118**, such as copper, iron, aluminum, tungsten and molybdenum, or alloys or compositions that, when struck by the electron beam **128**, radiate X rays **124** of varying frequencies which propagate to the sample

switched ON and OFF by a control circuit **136** to select the desired respective area of the anode **118** that will be struck by the electrons **128** to generate the X-ray wavelength desired. Although a list of elements has been enumerated above, other elements may also be used, this is a teaching that is well known to those skilled in the art. In applications where a single tailored spectrum is desired without variation, the compositionally varied anode **134** may manufactured to provide the desired spectrum when irradiated by emitters **117** that need not be separately gated.

The fields **128** between the cathode **116** and anode **134** determine the size and point of impact of the beamlet, and thus determine the X-ray source location and size attributable to that beamlet. The electron optics are optionally so that adjacent beamlets are essentially contiguous, overlapping, or separate. A single beamlet strikes the anode **134**, producing X rays **124** which exit the tube through the transmission cathode **116**. This process is repeated in succession, or concurrently, with other beamlets. The location of the X-ray sources for each beamlet is known from the geometry of the components including the cathode **116** and electron optics (not shown). The elemental composition of each successive anode source point **118** is known by design. The total X-ray spectrum is the sum of the spectra from the various source points. The anode **134** may contain multiple points of the same composition The spectral contribution of a particular composition may be enhanced by gating on more points of that composition, or by gating them on for longer periods of time.

The primary X rays **124** emitted by the transmission cathode tube **60** irradiate the sample **122**, which fluoresces according to well known physics. The fluorescence X ray **138** is detected by a spectral detector **142** whose output is captured by an analysis system, typical of those known in the art of X-ray spectral detection systems, and spectrally analyzed by computer to determine the chemical elemental composition of the sample. Spectral measurements are performed by the spectral detection system **142**. The spectral detection system **142** may be an energy dispersive (ED) detection system or a wavelength dispersive (WD) system. WD apparatus disperses the X rays in space, each wavelength to a different angle, using X-ray diffraction, e.g.,

from a crystal or multilayer. The detector in a WD apparatus need only count the number of photons arriving, as the wavelength is known from the angle at which the diffractor is tuned.

ED apparatus absorbs individual X-ray photons, converts the photon to an electrical pulse, quantifies the number of electrons in the pulse, and relates the pulse amplitude to photon energy. Photon energy E and photon wavelength W are related by the simple relationship EW = constant, where the value of the constant is well known (12.398 for E in kilo electron volts (keV) and W in Angstroms). Due to the mechanical simplicity of ED systems and their suitability for digital data capture, they are preferred in all but the most demanding work. The spectral measurements made by the detection system **142** are analyzed by a computer (not shown) to determine chemical elemental composition, using methods well known to those skilled in the art.

The function of an XRF system is to irradiate a sample with X rays to stimulate the sample to emit its own fluorescent characteristic X radiation **148**. It is advantageous for XRF analysis to be able to vary the primary X-ray spectrum illuminating the sample. At present, this is typically accomplished by irradiating the sample **144** with fluorescent x rays **148**, by use of x ray filters **144** or **147**, or by replacing the entire X-ray tube with one having a different anode material. A tube with tailored spectrum would obviate the need to rely on the lower intensity of fluorescence or filtered sources, and it would no longer be necessary to replace the tube simply to alter the spectrum.

In another preferred embodiment, X-ray fluorescence (XRF) systems employing transmission cathode X-ray tubes **70** and **80** , as shown in **Figures 5b** and **5c**, may differ in the placement of the detector **142**. The transmission cathode X-ray tubes **70** and **80** may have single or multiple composition anodes **146**. **Figures 5b** and **5c** show two typical optional placements of the detector **142**; only one detector **142** is necessary in a given system. **Figure 5c** shows a side view of an annular areal transmission cathode X-ray tube

a larger area of anode, enabling higher total output X-ray power. XRF systems do not require spatial resolution, so a small source is not required. The areal transmission cathode X-ray tube achieves these advantages.

A transmission cathode tube may be configured to operate as an electron microprobe **90**, as shown in **Figure 6a**. An electron microprobe is a large laboratory instrument similar to a scanning electron microscope (SEM) that scans a beam of energetic electrons onto micrometer areas of a sample to produce characteristic x rays that are detected by a non-imaging spectral detection system. These characteristic X rays are not fluorescent X rays, for fluorescence results from photon (i.e., X ray) excitation not electron excitation. However, the X-ray emission wavelengths are the same in the two cases, so the detection and analysis subsystems may be identical to these used for XRF. Both methods of excitation are useful for the spectral determination of chemical elemental composition. The emitted characteristic X rays may be detected by an ED or WD X-ray detection system and analyzed to determine the chemical composition of the sample, as with fluorescence x rays. Electron probe imaging has become so popular that X-ray detection attachments are commonly found on laboratory SEMs. Contemporary electron microprobes have higher electron beam currents than typical SEMs, and likely also have a larger focal spot on the sample.

A conductive sample **152** that withstands vacuum conditions may be placed in the anode **154** position of a transmission cathode X-ray source **90**. X rays **156** emitted by the electron-irradiated sample **152** are detected by an external, non-imaging, spectral detector **158** viewing the sample through the transmission cathode **162**. For a system with a gatable and addressable transmission cathode **164**, the image of the sample **152** and anode **154** is acquired by scanning the cathode array **162**. The compositionally structured anode **134** is now the sample **152** in **Figure 6a**, and gating is performed on small groups or individual electron emitters **164** in **Figure 6a** rather than on regions or larger areas of emitters **117** as in **Figure 5a**. The X-ray detector **158** is located outside the probe **90**. Either ED or WD detection or both may be used. (The entire sample **152** may be compositionally analyzed at once but without spatial imaging by activating all

electron emitters **164** simultaneously in area illumination.)

A gatable and addressable transmission cathode **162** may be scanned. Successive electron emitters **164** are scanned, each producing an electron impact point on the sample **152** or anode **154**, X rays **156** emitted by the electron impact **154** point are recorded digitally in a computer **168** as an image. When a spectum recording detector is used, the recorded image is an array of spectra known as a hyperspectral image cube. The image cube may be analyzed and displayed as a compositional map of the sample on a computer monitor screen **172**; various mappings are possible for a sample containing multiple chemical elements. A single detector **158** may measure many or all X-ray **156** source points in succession. Multiple detectors **158** may view the source points to achieve particular additional advantages. For example, different X-ray filters (not shown) may be applied to the different detectors **158**, or different types of detectors **158** with differing response characteristics may be employed as an aid to enhancing the quality or speed of data acquisition.

The imaging granularity of the scanning electron microprobe **90** will be limited by the spacing between emitters in the cathode array **162**. While this spacing is larger than the resolution achievable with large, laboratory sized instruments, the simplicity of construction, small size, and suitability for microfabrication offer significant advantages for particular applications which the large and costly laboratory sized instruments cannot meet.

In another preferred embodiment, as shown in **Figure 6b**, the image granularity of the scanning electron microprobe **100** may be reduced by the addition of elements, such as electrostatic deflection plates **174**, to control the scan of the electron beamlet **176** over distances less than the spacing interval. An electron beamlet **176** may then be placed controllably on intermediate points on the sample **178**, between the home impact areas that adjacent beamlets **176** would impact if no deflection were applied. For example, electrostatic deflection plates **174**

beams that may be transiting the tube **100**. By varying the

deflection voltages **182**, the deflected beamlet **176** can be made to strike its own home impact area, that of its neighbor, or any intermediate point, whereby finer positioning than the source spacing is achieved. In addition, redundancy is achieved, whereby the same area of sample **178** may be addressed by neighboring beamlets in succession by use of deflection circuitry applied to the deflection plates **174** and gate and scan control circuitry **184** applied to the transmission cathode **186**.

In another preferred embodiment, as shown in **Figure 6c**, multiple source points of a collimator imaging probe system **110** may be activated simultaneously. The sample **186**, in the anode **188** position, is again illuminated directly by electrons **192** to generate characteristic X rays **194** from the sample **186**. The collimator **195** preserves the X-ray emission image of the sample **186** onto an imaging detector **196**. A spectral imaging detector may also be used to collect a hyperspectral image cube.

In another preferred embodiment, as shown in **Figure 6d**, having a scanning transmission cathode with anode-window electron probe **120**, where an anode **198** is fabricated having sufficiently thin regions, or fabricated of a sufficiently thin material such as thin beryllium metal foil, the electrons **202** may be accelerated from the cathode through the anode **198** and into an external volume containing a sample **206**. The transmission cathode **208** and electron optics (not shown) may then be completely sealed and maintained clean of possible outside contaminants. The sample **206** is placed close to the anode-window **198**. The volume holding the sample **206** may be evacuated to facilitate electron **202** transit to the sample **206**, while retaining the benefits of a sealed source tube **204**. Alternatively the volume holding the sample **206** may be filled with a low density or low atomic number gas. The transmission cathode **208** may be scanned or activated on an areal basis using a gate and scan control circuitry **218**, as in the previous examples. X rays **214** emitted by the sample **206** are transmitted through the sample **206** holding volume, through the anode-window **198**, through the transmission cathode **208**, and detected by a first detector **216**. Also X rays **212** emitted by a sufficiently thin sample are transmitted to a second detector **222**. Scanning the transmission cathode **208** can be used to image the composition of the sample **206**, as before, using a first

detector **216** or a second detector **232**.

In another preferred embodiment, an X-ray probe tube **130**, as shown in **Figure 7**, is outfitted with an anode-window **226** of higher atomic number (Z) and greater mass thickness, an X-ray probe may be produced. The probe **130**, includes a scanning transmission cathode **228** and the higher Z anode-window **226** in an evacuated, sealed or pumped tube **244**. As the electron beamlets **232** scan across the anode-window **226**, the anode-window **226** emits primary X- rays **234** from successive impact points. The scanning is controlled by the use of gate and scan control circuitry **252**. The scanned anode-window **226** becomes a scanned X-ray source.

A sample **236** placed in close proximity to the anode-window **226** may also emit characteristic fluorescent radiation in all directions and may be viewed by variously placed X-ray detectors. Fluorescent X rays **248** from the sample **236** that transit through the anode-window **226** and through the transmission cathode **228** may be detected by a first detector **238**. Fluorescent X-ray emissions **245** from the sample **236** may be viewed in transmission through the sample by a second X-ray detector **246** in the Sample Transmission position. More highly absorbing portions of the sample **236** will present weaker transmitted fluorescent X-ray signals **245** to the second detector **246**. Alternatively, an areal imaging detector (not shown) may likewise be placed in close proximity to the sample **236** to receive and, by collimator or contact radiography, record the X- rays **245** transmitted through the sample **236** to the areal imaging detector.

Both detectors **238** and **246** will also view the anode-window **226** source. Much of the intensity of unwanted X rays **242** from the anode-window **226** source may be reduced for the Sample Transmission detector **246** by moving the detector **246** off axis, as shown, and interposing a suitably fine collimator (not shown) between the anode-window **226** and the sample **236**.

In an arrangement not shown, the transmission cathode X-ray source may be used in point projection radiographic imaging systems. For radiographic systems, a small X-ray source (not

source, the areal cathode's **274** electron current can be focused to a small area on the anode **276**, using additional whole-beam focusing elements (not shown) to shape the fields within the tube (not shown), as is well known to those skilled in the art of electron focusing. The limitations on X-ray power delivered by point source X-ray tubes (not shown) are set by the temperature at which the anode **276** metal vaporizes or melts. The lifetime of the common filament tube is often determined by the lifetime of the filament. The areal transmission cathode **274**, with convergent electron beam geometry to produce a point focus, offers redundancy in the electron source, extended cathode **274** life and thus greater tube life.

In another preferred embodiment , as shown in **Figures 8a** and **8b**, an areal transmission cathode X-ray tube **140** and **150**, respectively, used for X-radiography, performs the function of graphically imaging a sample with X-ray illumination, e.g., a chest X-radiograph. Because an image is formed, an imaging detection system **254** is required. Areal X-ray sources are infrequently used in radiographic imaging systems. Areal sources require collimation to refine the image resolution. An X-ray collimator **272** is analogous to venetian blinds, allowing view for some angles but not for others. X-ray collimators **272** are made in various geometries. Soller slits are a stack of planar absorbing sheets separated by open spaces through which X-ray transmission is permitted. Tube collimators **272** are a stack of tubes; X rays pass through the centers of the tubes and in the open spaces between tubes. Square cylindrical tubes are also used for X-ray collimation, as are hexagonal structures. The basic concept with collimators **272** is to make the acceptance angle of the collimator **272** sufficiently small that the image is resolved, but as large as permitted so as to retain as much X-ray flux **268** as possible.

Three key features of collimators **272** for X-ray imaging are (1) collimators **272** function by absorbing X rays **268**, (2) collimators **272** require areal sources to be effective for imaging, and (3) collimator **272** imaging arrangements can be very compact. X-ray sources of large enough size to be of interest for compact collimator **272** imaging have not generally been available. X rays **268** absorbed by the collimator **272** are of no value, and the power used in producing them becomes lost power. Here, the

salient parameter is local source brightness more than total output power. For these reasons, collimators **272** are rarely used for imaging.

The transmission cathode **274** makes large area X-ray sources a possibility, and therefore makes compact collimated X-radiography a possibility. Losses due to X-ray **268** absorption in the collimator **272** remain an issue, as does the brightness of individual source elements. A collimator X-ray imaging system **150** and **160** with an areal transmission cathode source **274** can achieve constant incident intensity across a large sample **262** to be imaged in a compact arrangement.

The collimator **272** for the X ray source may be located in any of several possible locations. **Figure 8a** shows the collimator **272** between the transmission cathode tube **274** and the sample **262**. In **Figure 8b**, the collimator **272** is shown between the sample **262** and the imaging detector **254** . The collimator **272** may also be included within the X-ray tube (not shown).

In another preferred embodiment, as shown in **Figure 9a**, a scanning electron imaging system **160** in which the sample **278** is placed at the anode **282** position of an evacuated tube **284** has an addressable cathode array **286** of gatable electron emitters **292**. Control of the gating of the gatable electron emitters **292** is provided by the use of circuitry for gating and scanning, according to techniques that are well known to those skilled in the art. The electrons **302** emitted by the cathode **286** are primarily electrons. As each emitter **292** is addressed in turn, scattered and other emitted electrons **294** emanating from the sample **278** or anode **282** are collected by electrodes within the tube **284** utilizing circuitry for collecting sample **278** scattering and emission current within the tube **284**, for example the unaddressed gate electrodes **286**, and recorded to form an image of the sample **278** and anode **282**. Regions of the sample **278** that cause many electrons **302** to be collected will appear differently in the image than regions that cause few electrons **302** to be collected. Compositional as well as topographic variations are

[illegible] may be collected and imaged in a similar fashion. Sample current is that part of

the primary electron current **246** that is collected by the sample **278** or anode **284**. The accelerating voltage of the emitted cathode electron beamlets **302** may be greater than or less than the voltages required for an X-ray emitting tube. For lower accelerating voltages, the sample **278** may optionally be placed closer to the cathode array **286**. The X-ray transmission properties of the cathode **286** are not of concern for the operation of this tube as an electron imaging system. This system requires no magnetic lenses for focusing and no deflection electrodes to accomplish raster scanning. Raster scanning is accomplished by addressing the cathode, and collimation is provided to the beamlets **302** by the gate electrodes **292** or other electrode structures as is well known to those skilled in the art. An electron imaging system **160** is thereby achieved in a device with simplicity of design, manufacture, and use.

In **Figure 9b**, a cross section of a miniature scanning electron imager **170** is depicted in which additional elements are added for the purpose of enabling or improving the detection of electrons **442** from the sample **418**. The cathode **424** may be either absorbant or transmissive to x rays. The gatable electron sources **425** may be any of various varieties of electron sources, including field emitters, photoemitters, thermoemitters, or other types of electron emitters. Individual emitters or groups of emitters are gated sequentially. For purposes of illustration, multiple beamlets **422** of electrons are emitted by the electron emitter **425** under control of electron source gating and control circuitry **423**. The beamlet **427** electrons are accelerated toward the anode **428** and a sample **418** by high voltage **432** in an evacuated enclosure **432**. The beamlets **427** impact a sample **418** or the anode **428** to produce secondary electrons emanating from the sample or anode, and some of the incident electrons in the beamlet **422** are backscattered **420** by the sample or anode. Some of the secondary electrons and back scattered electrons are collected or detected by electron detectors **426**. The signals from electron detectors **426** are received and processed by electron detector circuitry **434** to form an electron image of the sample **418**. The electron detectors **426** may be any of various varieties of electron detectors well known to those skilled in the art.

Additional elements may be added, singly or in combination,

to provide improved electron detection or improved electron beam handling or both, such as in a miniature scanning electron imager **180**, as illustrated in **Figure 10**. Devices for electron collection and detection may be added as shown, whether on existing substrates or on new substrates or holders, and placed in a manner not to impede the primary electrons or beamlets **428** but to collect the electrons **802** back scattered or secondary electrons emanating from the sample **432** or anode **434**. These devices for electron collection and detection may rely on scintillation, or direct charge collection performed by devices such as silicon devices or Faraday cups or conducting electrodes, or may rely on electron amplification performed by devices **438** such as electron multipliers, channel electron multipliers, microchannelplates, and the like. The electron collection and detection devices **438** are connected to electronics for processing the detected signal. The electron collection and detection devices **438** may have the facility to accelerate or decelerate electrons **436** from the sample **432**, by application of suitable voltages to the devices themselves or to electrodes or screen grids **436** or the like placed between the devices**438** and the sample **432**. Additional elements **804** may be optionally added for controlling the beamlet **428** beam profile, such as ring shaped electrodes, hollow cylindrical conducting electrodes, or other elements of shapes well known to those skilled in the art of electron optics to be effective for controlling beam **428** profile by means of electric fields, or such as magnet coils or magnets for controlling beam profile by means of magnetic fields. Further elements **806** for controlling the deflection of individual or multiple beamlets **428**, with associated deflection electrical control circuitry, may be optionally added as illustrated in **Figure 10**. Provided the cathode **442** of the imager **180** of **Figure 10** is a transmission cathode, the imager **180** may further be used as an electron microprobe when outfitted with X-ray detection.

It is to be understood that elements for controlling beam profile or beam deflecting or electron collectors or electron

In a preferred embodiment of the variant transmission cathode, a different diamond electron field emitter **190** may be employed as a transmission cathode, as shown in **Figure 11**. See, Normile, FIELD EMITTERS FINDING HOME IN ELECTRONICS, Science, Vol. 281, pp. 632-633, 31 Jul 98 and Kang et al., ULTRALOW BORON-DOPED DIAMOND FIELD EMITTER VACUUM DIODE, Elect. Dev. Ltrs., Vol. 19, No. 10, pg. 379, Oct. 98. A cover device **296** of silicon, on layer of silicon oxide **304** which has been deposited on a glass substrate **306**, encompasses a diamond emitter diode **298** and over each diode **298** is an opening **302** to allow passage of electrons **301** to the anode **303**. In other designs, metal gate electrodes are used as positive electrode for field extraction and collimation of the electron beam. Other types of field emitters, not involving diamond, may also be used in transmission cathodes.

The ability to make micro-heaters has been amply demonstrated in the microelectronic mechanical systems (MEMS) teachings. Arrays of such micro-heaters can be used as thermionic electron sources, with total areas much larger than the area of a typical drawn filament. Micro-heater thermionic electron sources may be switched by controlling the heater currents for each source. Electrostatic switching of the emitted electrons remains as an available switching option which may be implemented. Two emission controls are them available: heater current and gate potential. Electron emitters based on thermionic emission may be used as electron emitters in transmission cathodes, or in electron imaging, as taught herein,

A hybrid approach could use field emission aided by moderately elevated temperature, i.e., significantly lower temperature than those at which drawn wire filaments are typically operated, yet above the ambient. This hybrid approach removes some of the disadvantages of high temperature. As above, two parameters are available for controlling beamlet current, namely emitter potential and emitter temperature.

A photoemitting cathode may be used, which includes a suitable substrate holding a photomissive material on its surface inside the X-ray tube. The substrate may be monolithic. A light source is arranged to illuminate the photoemitter with sufficiently energetic photons as to stimulate electron emission. As X rays are themselves sufficiently energetic photons as to

stimulate photoemission, even from metallic surfaces, the emitted X rays will aid in the continued operation of the device, provided they impinge on photoemitting material. By using a microchannel plate electron multiplier in conjunction with the photocathode, the X rays absorbed by the cathode (or microchannel plate) can stimulate electron emission which will supply the anode with sufficient emitted electrons to maintain a self-sustaining X-ray intensity on the cathode. The emission may be ceased by removing the high voltage or restricting the cathode current, thus preventing the electrons from reaching X-ray emitting energies. Electron emitters based on photoemission may be used as electron emitters in transmission cathodes, or for electron imaging, as taught above.

In a micro-photoemitter array design in which the photoemissive material is patterned on the cathode in an array geometry, the array elements may be selected and gated on by virtue of their being illuminated by photons. Alternatively, the emitted electrons from photoemitters may be electrically gated as with other methods of emission. In yet another alternate, each array element may incorporate a photoswitch which, upon illumination, causes a gate voltage to be applied to the respective electron emitter, which then emits. Selection or scanning of individual elements or areas can be performed by illuminating or masking of photoswitches that apply gate voltages.

Other elements, including metal conducting layers, doping layers, and other electron emitter designs may be used in variant electron emission designs. For transmission cathodes, the resulting structure must meet the criterion of being transmissive to X rays. The various electron emitters disclosed for transmission cathodes may also be applied for electron imagers and X-ray probes.

The use of areal electron emission from an array of electron emitters reduces the current requirements on each electron source. The current requirements are closely linked to longevity

including electron emitters can be fabricated directly on or spanning small gaps on various substrates, such as silicon or others. Microfabrication can be carried out with virtually any class of material, including metal conductors, insulators, or semiconductors. Each micro electron source produces a beamlet of electrons. Microsources can be arranged in arrays or formed in patterns of any suitable shape.

X-ray diffraction applications typically make use of only small angular segments of the x rays emitted by X-ray tubes. This is a natural consequence of the small range of incident and reflected angles (typically much less than a degree of arc) over which the conditions are satisfied for X-ray diffraction by optics such as crystals. This, combined with the relatively small source size of X-ray tubes, leads to the restriction that diffracted X-ray beams are low power and small. The small size of diffracted beams has been addressed by Boettinger, et al., who taught a method of using asymmetric diffraction to expand the cross section of a diffracted beam to sizeable and useful extent, with an associated lowering of the power per unit area of the beam. (SEE W.J. Boettinger et al., X-ray MAGNIFICATION, Rev. Sci. Instrum., Vol50, No. 1, pp.26-30, 1979). Alternately, the Boettinger technique can be used in reverse to reduce the cross section but increase the power per unit area of the beam. One crystal is required for each dimension in which an X-ray beam size alteration is to be carried out. Any diffractor from which asymmetric diffraction may be produced can be used in a Boettinger arrangement.

In another preferred embodiment, as shown in **Figure 12, 200** areal transmission cathode tube **502** offers a means for producing X rays from a large area. The total power emitted from an areal transmission cathode tube **502** can exceed the power available from a standard X-ray tube, without overheating the anode **504**. This larger source may then be diffracted by a crystal or other diffracting optic **506** to irradiate larger areas with greater X-ray power than previously available. By application of the Boettinger technique in reverse, as depicted in **Figure 12**, the diffracted rays **508** from a large area transmission cathode tube may be reduced in cross section and increased in power density to values previously not readily available in the laboratory. By

application of the forward Boettinger technique with an areal transmission photocathode X-ray tube, exceptionally large beams of monochromatic radiation may be produced.

Although the invention has been described in relation to the exemplary embodiment thereof, it will be understood by those skilled in the art that other variations and modifications such as, any X-ray system may be used with X-ray filters to advantageously treat the X-ray spectrum to modify its properties in ways well known to those skilled in the art, can be affected in the preferred embodiment without detracting from the scope and spirit of the invention as set forth in the claims.

CLAIMS

What is claimed:

1. A transmission cathode comprising:

an X-ray transmissive material forming an X-ray window of such size that X rays will be emitted through the material; and

at least one electron emitter affixed to a surface of the X-ray window.

2. A transmission cathode X-ray tube for the generation of X rays comprising:

an evacuated tube;

a transmission cathode; and

an anode.

3. A device for the generation of X rays comprising:

an evacuated tube;

a transmission cathode;

an anode; and

means for generating an electron flow that propagates from the cathode to the anode, upon the flow of electrons striking the anode, a primary stream of X rays are generated that radiates out of the evacuated tube through the transmission cathode.

4. A device, as in Claim 3, wherein said tube is an enclosed tube.

5. A device, as in Claim 3, wherein said tube is a pumped tube.

6. A device, as in Claim 3, wherein the transmission cathode is a field emitter on a substrate, said field emitter and substrate being transmissive to X rays.

7. A device, as in Claim 6, where in the field emitter is made of a diamond material.

8. A device, as in Claim 3, wherein the means for generating an electron flow is an electron emitter and an accelerating potential for accelerating the emitted electrons between the

cathode and the anode.

9. An X-ray fluorescence measurement system comprising:

a transmission cathode X-ray tube for generating X rays; and

an X-ray detector for detecting fluorescent X rays from a sample external to the X-ray tube.

10. A device for the generation of X rays comprising:

an evacuated tube;

a transmission cathode having a plurality of electron emitting elements;

an anode;

means for generating an electron flow that propagates from the cathode elements to the anode, upon the flow of electrons striking the anode X rays are generated that radiate out of the evacuated tube through the transmission cathode.

11. A device, as in Claim 10, wherein the means for generating an electron flow is a plurality of electron emitters and an accelerating potential for accelerating the emitted electrons between the cathode and the anode.

12. A device for the generation of X rays comprising:

a evacuated tube;

a transmission cathode having a plurality of electron emitting elements;

an anode further comprised of a plurality of electrically conducting elements;

means for generating an electron flow that propagates from the cathode to elements of the anode, upon the flow of electrons striking a particular element of the plurality of electrically conducting elements of the anode X rays of a predetermined . frequency are generated that radiate out of the evacuated tube through the transmission cathode; and

means for controlling the selection of a particular element

1[illegible]. A device, as in Claim 1[illegible], wherein means for controlling the

selection of a particular element of the plurality of electrically conducting elements of the anode is a switching device that selectively biases a predetermined element of the anode with an accelerating potential between the cathode and the anode.

14. A device, as in Claim 12, wherein means for controlling the selection of a particular element of the plurality of electrically conducting elements of the anode is an electronic device for selectively gating electron emitting elements from the plurality of electron emitting elements of the cathode so as to allow emitted electrons to flow to a predetermined element of the anode, of the plurality of anode elements, as determined by an electric field within the device, a plurality of such anode elements having an accelerating potential between the cathode and the anode.

15. A method for generating X rays comprising the steps of:

generating an electron flow from a transmission cathode;

exciting X rays when said electron flow strikes an anode; and

radiating said X rays through the transmission cathode to a sample.

16. A gatable transmission cathode comprising:

an X-ray transmissive material forming an X-ray window of such size that X rays will be emitted through the material;

a plurality of electron emitters affixed to a surface of the X-ray window; and

means for gating the electron emitters so as to control an emitted electron current.

17. A gatable transmission cathode having rows comprising:

an X-ray transmissive material forming an X-ray window of such size that X rays will be emitted through the material;

a plurality of electron emitters affixed to a surface of the X-ray window disposed in a plurality of rows;

means for gating the electron emitters so as to control an

emitted electron current; and

means for selecting a predetemined row of electron emitters of the plurality of rows of electron emitters.

18. A device, as in Claim 17, wherein the means for gating the electron emitters so as to control an emitted electron current is a plurality of gate electrodes, each gate electrode being disposed to gate a single row of the plurality of rows of electron emitters.

19. A device, as in Claim 17, wherein the means for selecting a predetemined row of electron emitters of the plurality of rows of electron emitters is an electronic circuit for applying a gate voltage to the gate electrode of the selected row of the cathode so as allow emitted electrons to flow from the selected row.

20. A gatable transmission cathode having an array comprising:

an X-ray transmissive material forming an X-ray window of such size that X rays will be emitted through the material;

a plurality of electron emitters affixed to a surface of the X-ray window arranged in an array;

means for selecting a predetemined electron emitter of the plurality of electron emitters; and

means for gating the selected electron emitter so as to control an emitted electron current.

21. A device, as in Claim 20 wherein the means for selecting a predetemined electron emitter of the plurality of electron emitters is an electronic device for supplying a gate voltage to the gating means so as allow electrons to be emitted.

22. A gatable transmission cathode, as in Claim 20 further comprising a means for scanning the electron emitters of the transmission cathode.

emitters in an ordered sequence.

24. A device, as in Claim 20, wherein the means for gating the electron emitters so as to control an emitted electron current is a plurality of gate electrodes, each gate electrode being disposed to deliver a voltage contributing to the gating of at least one electron emitter, the gating of any invividual electron emitter being determined by the sum of the voltages contributed by all gate electrodes disposed to deliver a voltage to that electron emitter.

25. An electron probe system for generating X rays comprising:

an evacuated enclosure containing;

a gatable transmission cathode;

an anode; and

a facility for holding a sample in electrical contact with the anode, in a position where it can be struck by accelerated electrons generated by the transmission cathode;

means for scanning the electron emitters of the transmission cathode; and

a detector for detecting X rays emitted by the anode and sample.

26. An electron probe for generating X rays, as in Claim 25, further comprising a means for deflecting electrons on their trajectory between the transmission cathode and the anode and between the transmission cathode and the sample.

27. An electron probe, as in Claim 26, wherein the means for deflecting electrons are deflection electrodes supplied with an electrical potential.

28. A transmissive anode electron probe comprising:

an evacuated tube containing;

a gatable transmission cathode; and

an anode transmissive to electrons;

whereby a sample may be located outside of the evacuated tube in a position where it can be struck by electrons generated by the transmission cathode and transmitted by the anode; and

means for scanning the electron emitters of the transmission cathode.

29. A transmissive anode X-ray probe comprising:

an evacuated tube containing;

a gatable transmission cathode; and

an anode transmissive to X rays;

whereby a sample may be located outside of the evacuated tube in a position where it can be struck by X rays generated by the transmissive anode; and

means for scanning the electron emitters of the transmission cathode.

30. A collimator imager comprising;

a transmission cathode X ray tube; and

a collimator allowing only those X rays forming an image of the transmission cathode X-ray tube to reach the image location.

31. A scannable cathode comprising:

a plurality of electron emitters affixed to a surface of a substrate;

means for selecting a predetermined electron emitter of the plurality of electron emitters; and

means for gating the selected electron emitter so as to control an emitted electron current.

32. A scanning electron imager comprising:

an evacuated enclosure further comprising;

a scanable cathode for generating electron emissions;

an anode; and

an electron detector; and

means for generating an electron flow that propagates from the cathode to the anode.

33. A scanning electron imager, as in Claim 32, further comprising a means for deflecting electrons on their trajectory between the scannable cathode and the anode.

35. A scanning electron imager, as in Claim 32, further comprising a means for retarding electrons on their trajectory between the anode and the electron detector.

36. A method of constructing a transmission cathode comprising the steps of:

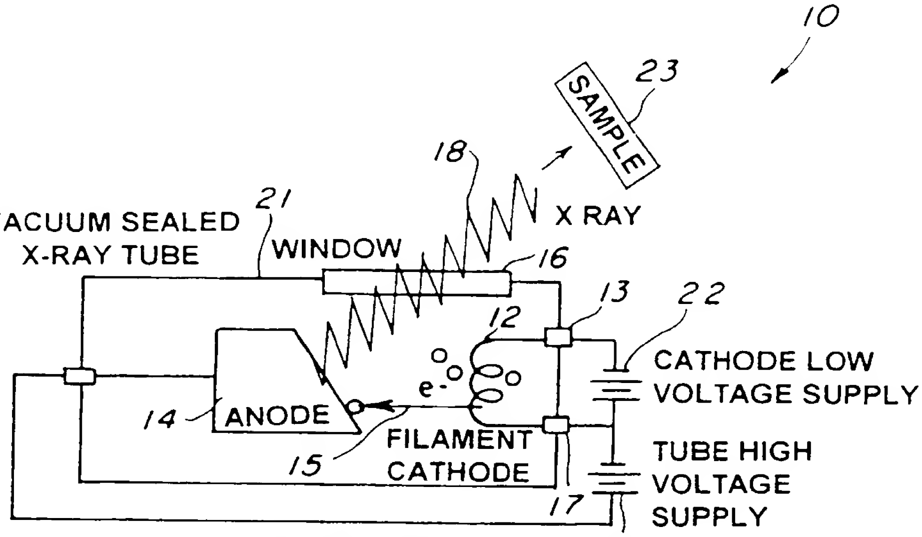
selecting an X-ray transmissive material to form an X-ray window of such size that X rays will be emitted through the material; and

affixing at least one electron emitter to a surface of the X-ray window.

37. A monochromatic X-ray source comprising:

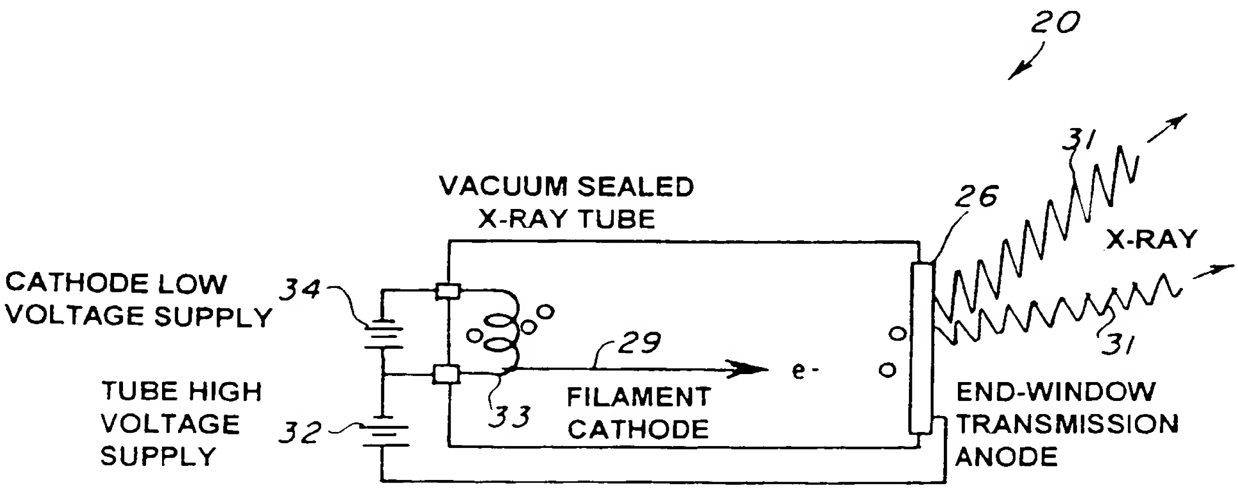
a transmission cathode X-ray tube; and

at least one asymmetrically diffracting X-ray optical element.



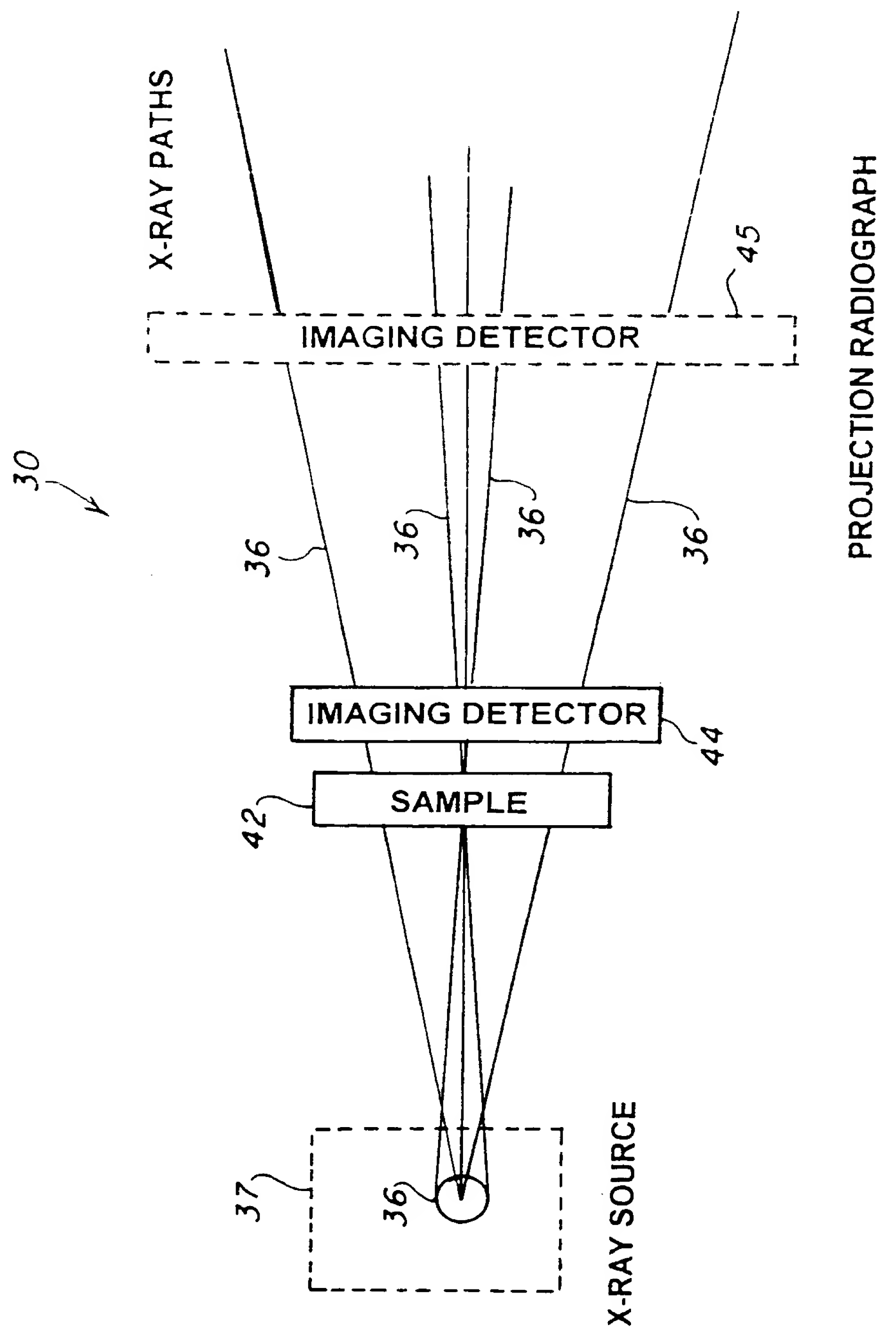
PRIOR ART

FIG. 1a



PRIOR ART

FIG. 1b



PRIOR ART

FIG. 1c

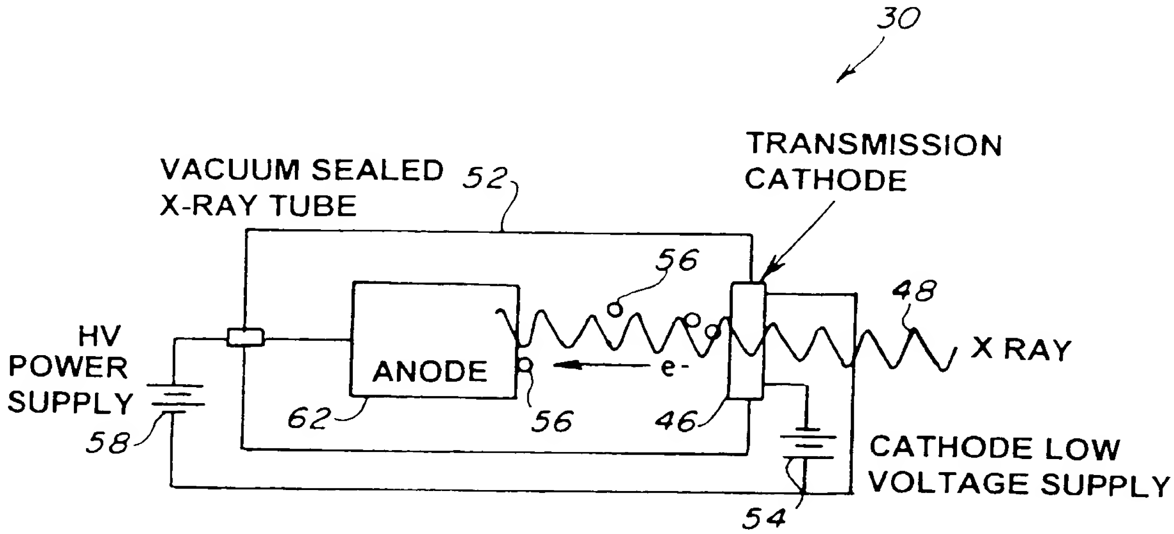

30
VACUUM SEALED
X-RAY TUBE
52
TRANSMISSION
CATHODE
56
48
HV
POWER
SUPPLY
ANODE
e-
X RAY
62
56
46
58
CATHODE LOW
VOLTAGE SUPPLY
54

FIG. 2a

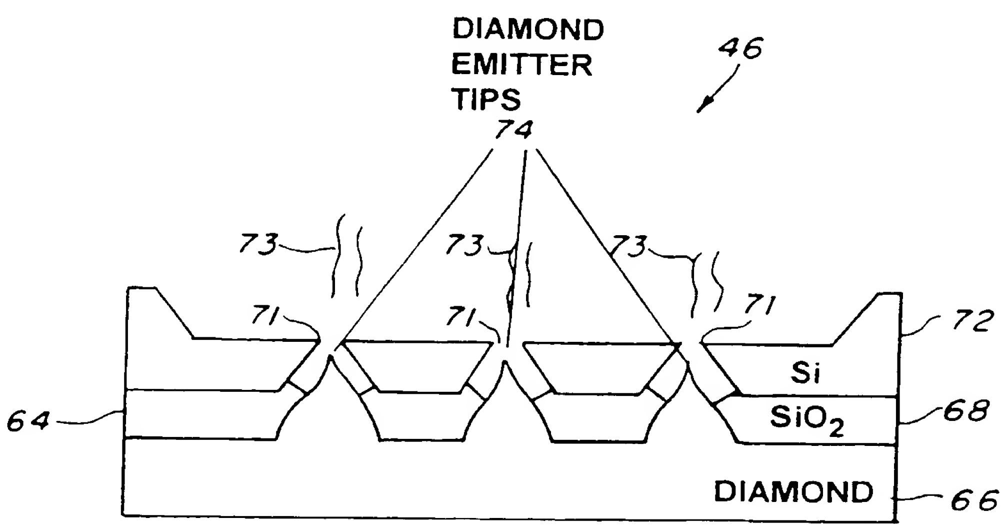

DIAMOND
EMITTER
TIPS
74
46
73
73
73
71
71
71
72
Si
64
SiO_2
68
DIAMOND
66

FIG. 2b

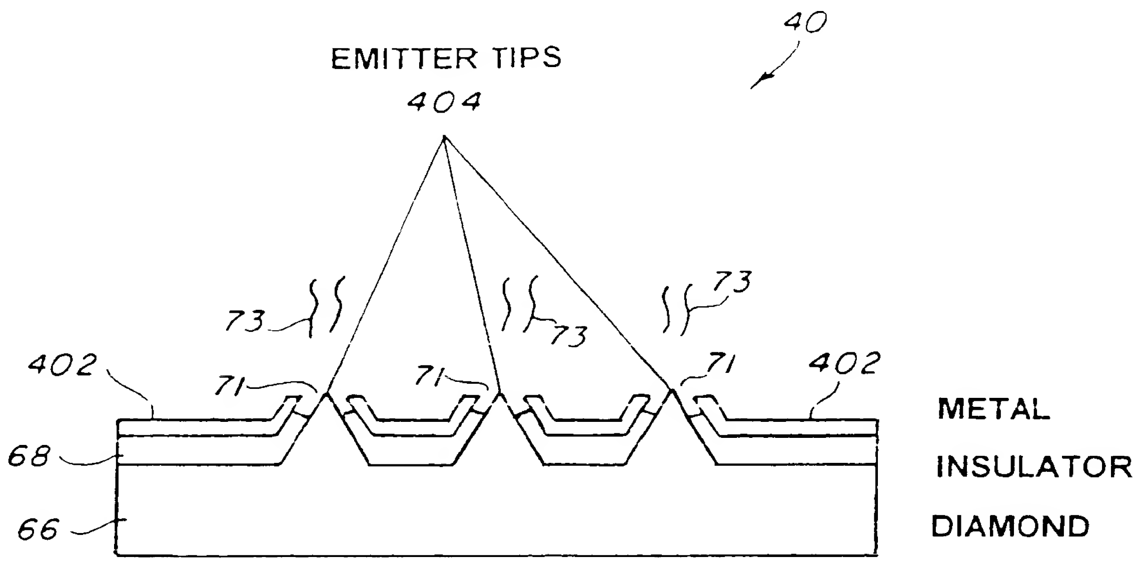

40
EMITTER TIPS
404
73
73
73
402
71
71
71
402
METAL
68
INSULATOR
66
DIAMOND

FIG. 2c

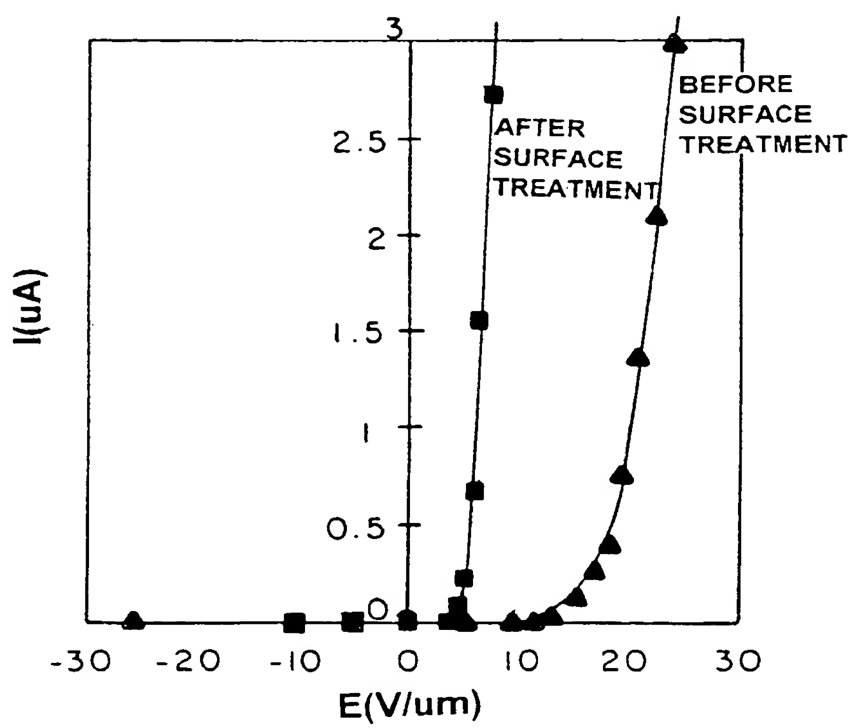

3
2.5
2
1.5
1
0.5
0
I(uA)
AFTER SURFACE TREATMENT
BEFORE SURFACE TREATMENT
-30 -20 -10 0 10 20 30
E(V/um)

FIG. 2d

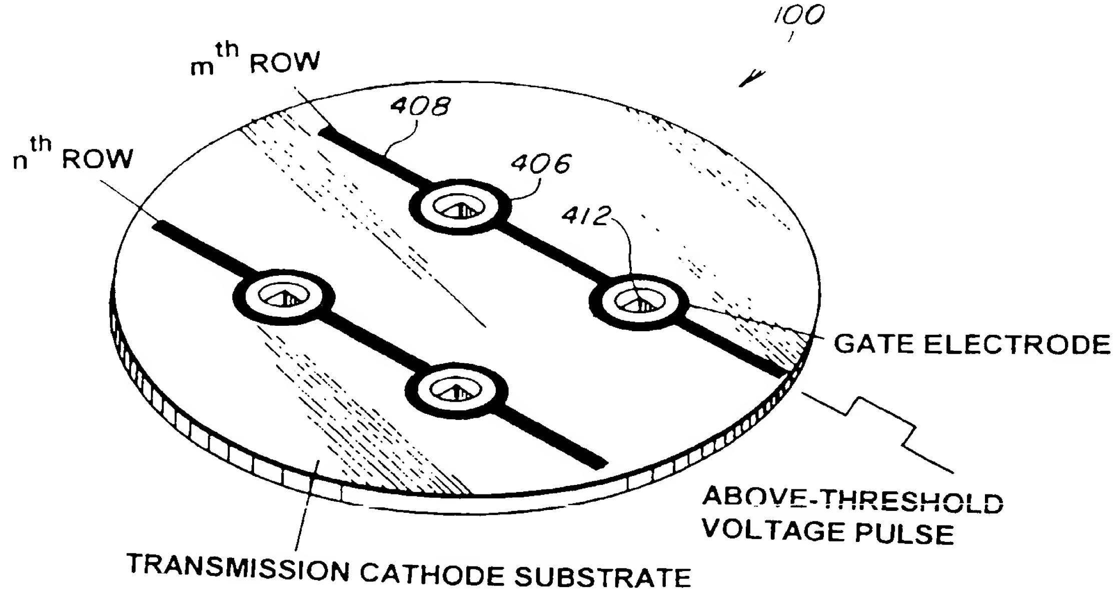

100
mth ROW
nth ROW
408
406
412
GATE ELECTRODE
ABOVE-THRESHOLD
VOLTAGE PULSE
TRANSMISSION CATHODE SUBSTRATE

FIG. 2e

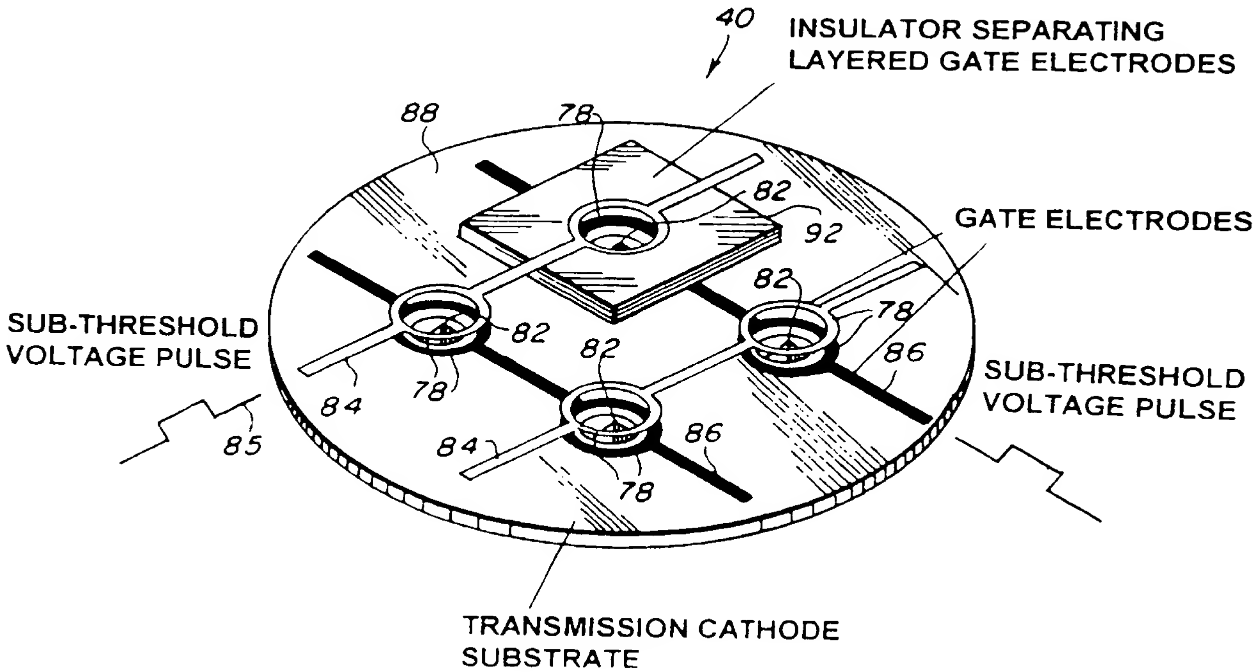

40
INSULATOR SEPARATING
LAYERED GATE ELECTRODES
88
78
82
92
GATE ELECTRODES
82
78
SUB-THRESHOLD
VOLTAGE PULSE
82
82
86
84
78
85
84
86
78
SUB-THRESHOLD
VOLTAGE PULSE
TRANSMISSION CATHODE
SUBSTRATE

FIG. 2f

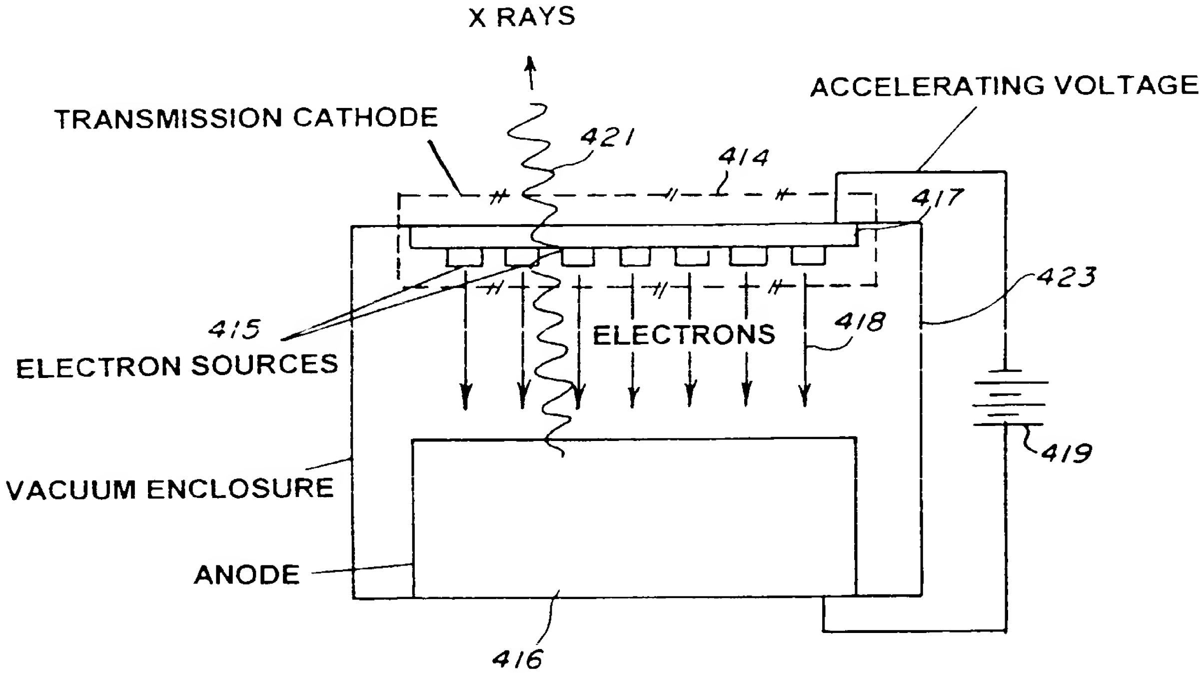

X RAYS
ACCELERATING VOLTAGE
TRANSMISSION CATHODE
421
414
417
423
415
ELECTRON SOURCES
ELECTRONS
418
419
VACUUM ENCLOSURE
ANODE
416

FIG. 3

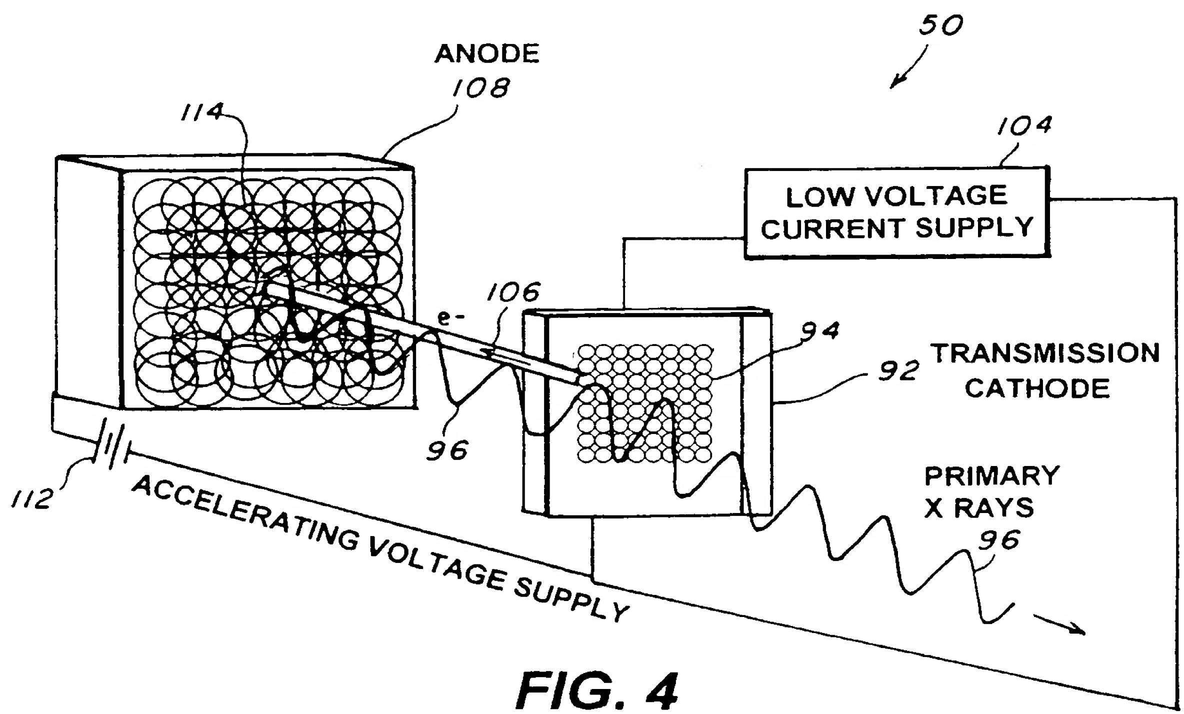

50
ANODE
108
114
104
LOW VOLTAGE
CURRENT SUPPLY
106
e-
94
92
TRANSMISSION
CATHODE
96
112
ACCELERATING VOLTAGE SUPPLY
PRIMARY
X RAYS
96

FIG. 4

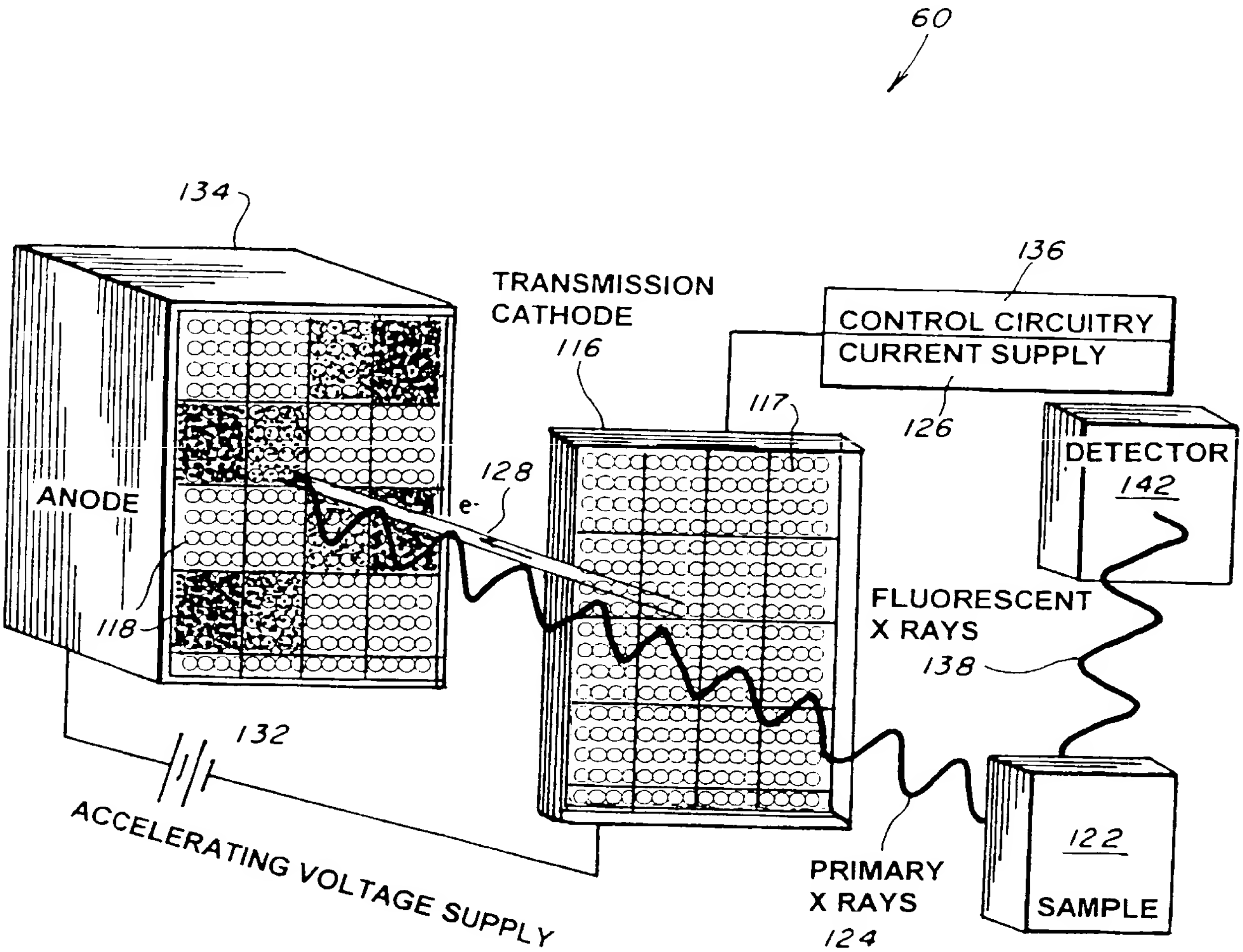

60
134
TRANSMISSION
CATHODE
116
136
CONTROL CIRCUITRY
CURRENT SUPPLY
126
117
DETECTOR
142
128
e-
ANODE
118
FLUORESCENT
X RAYS
138
132
ACCELERATING VOLTAGE SUPPLY
PRIMARY
X RAYS
124
122
SAMPLE

FIG. 5a

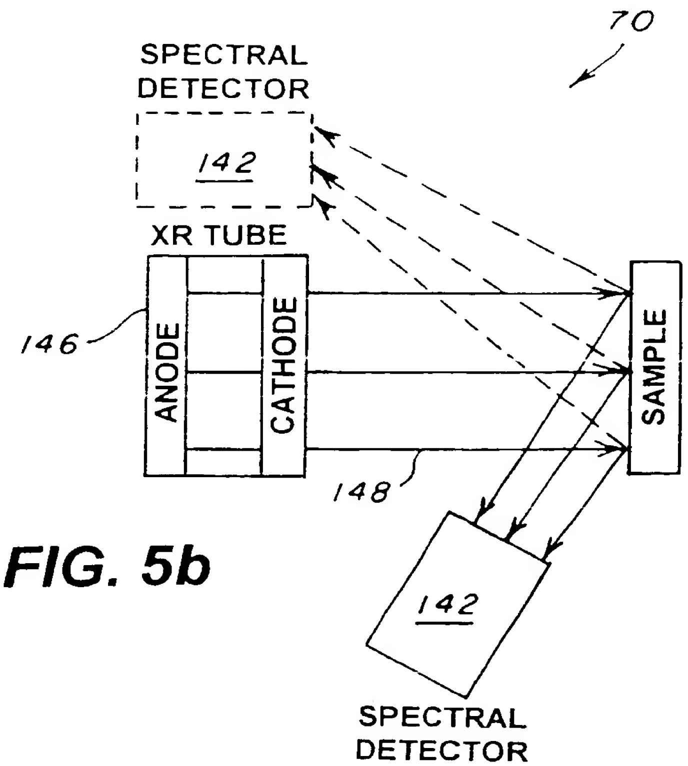

70
SPECTRAL
DETECTOR
142
XR TUBE
146
ANODE
CATHODE
SAMPLE
148
142
SPECTRAL
DETECTOR

FIG. 5b

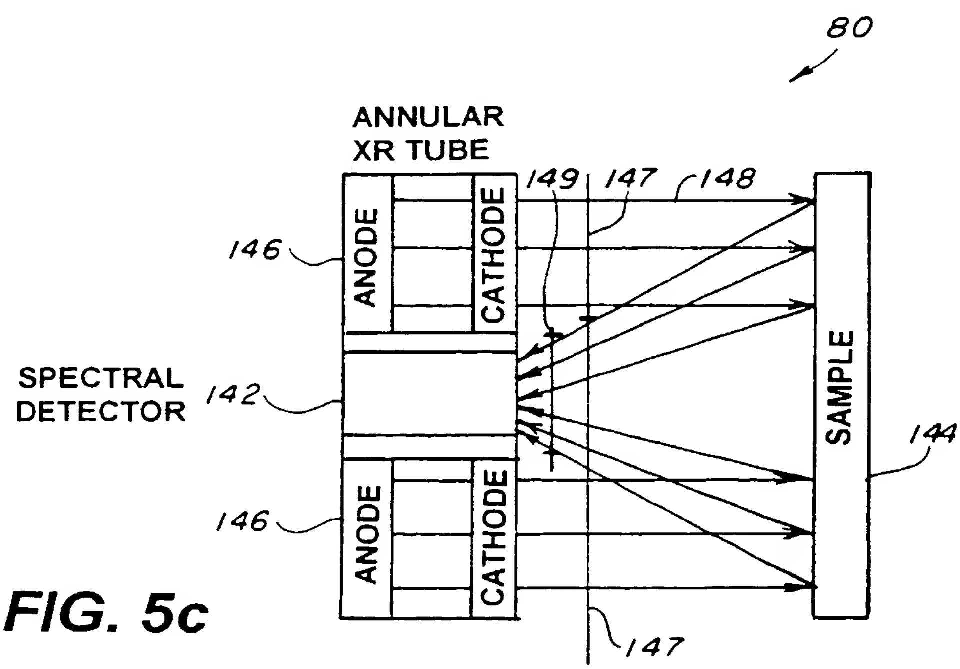

80
ANNULAR
XR TUBE
149
147
148
146
ANODE
CATHODE
SPECTRAL
DETECTOR
142
SAMPLE
144
146
ANODE
CATHODE
147

FIG. 5c

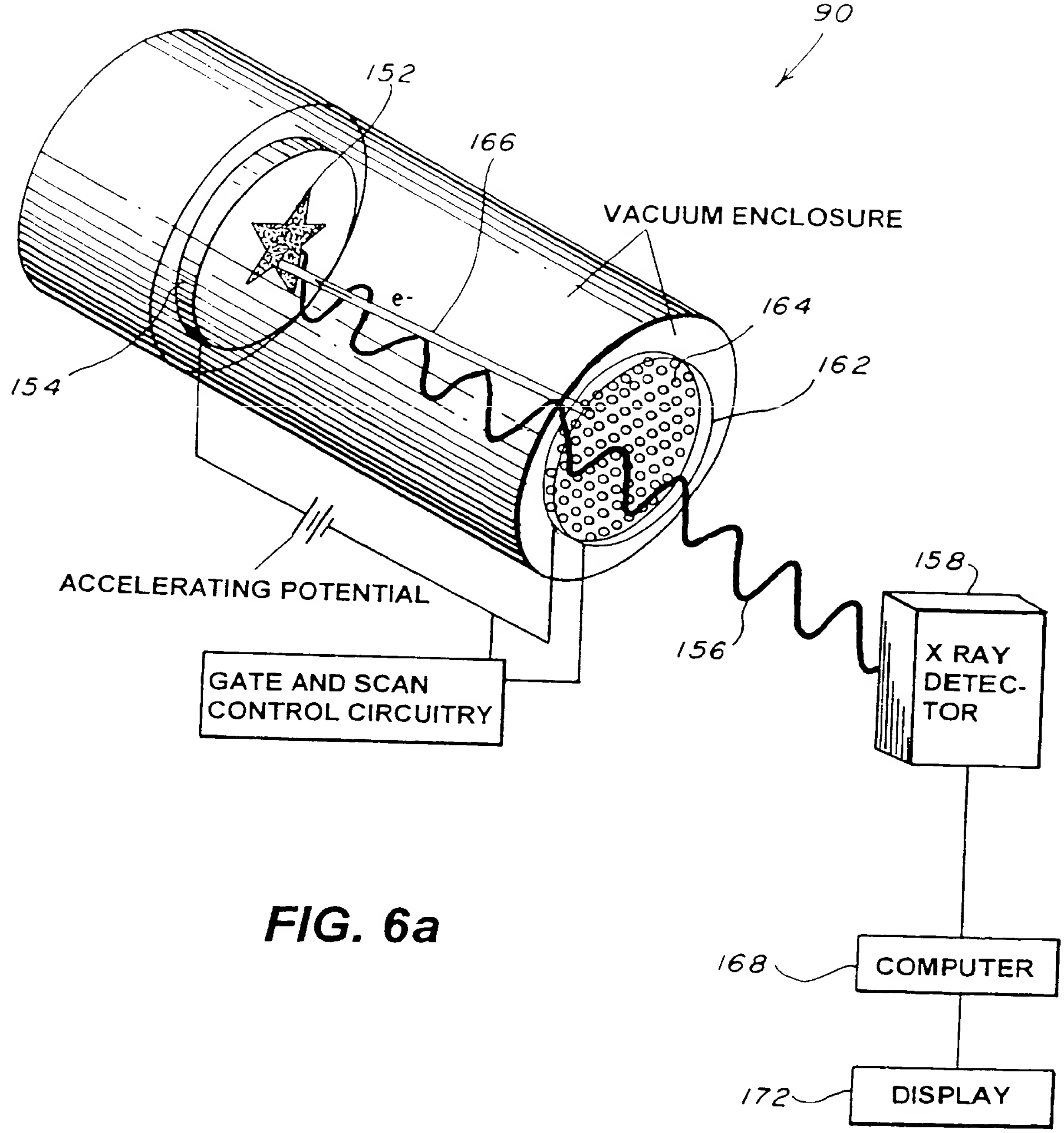

90
152
166
VACUUM ENCLOSURE
e-
164
162
154
ACCELERATING POTENTIAL
GATE AND SCAN CONTROL CIRCUITRY
156
158
X RAY DETECTOR
168
COMPUTER
172
DISPLAY

FIG. 6a

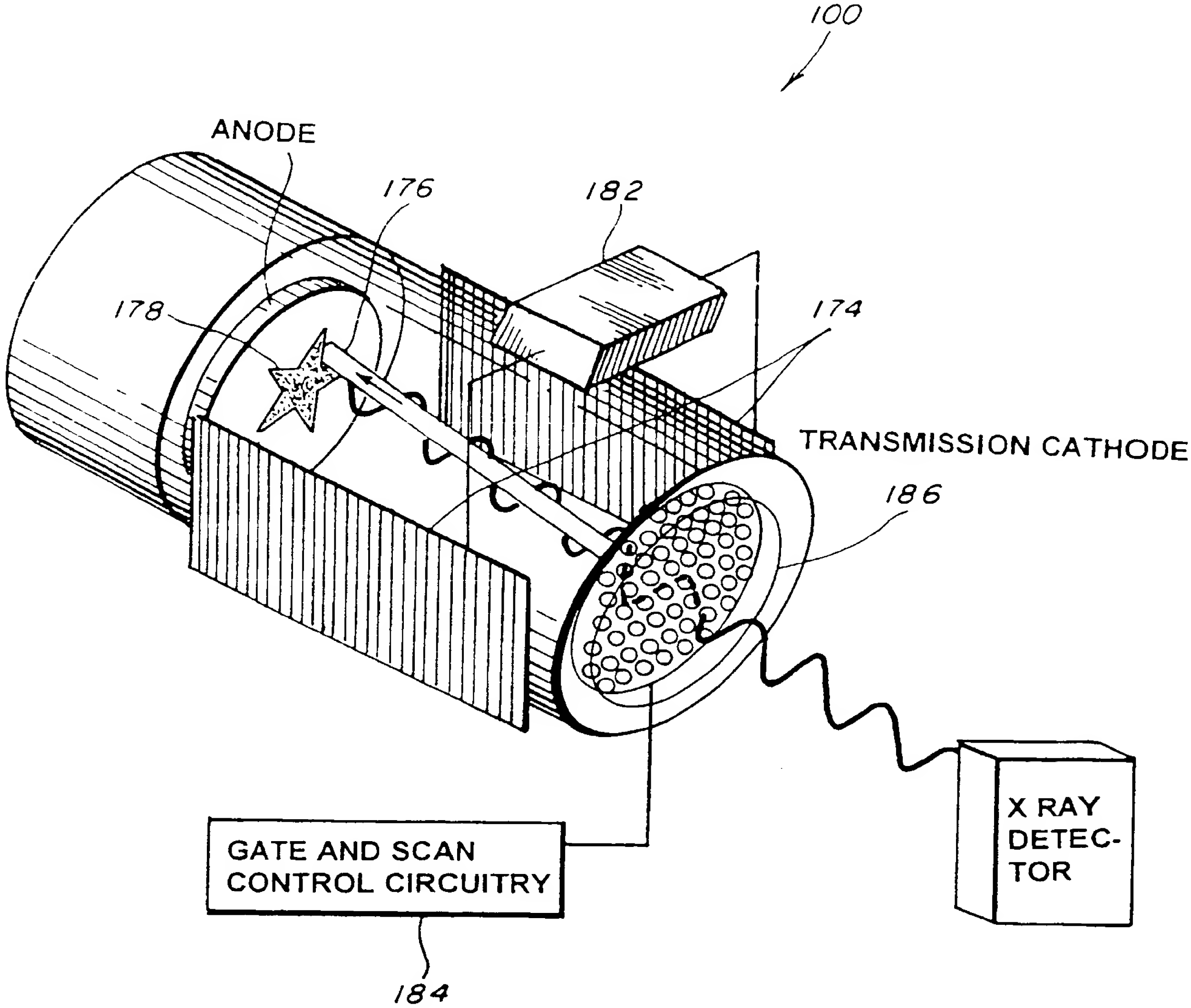

100
ANODE
176
182
178
174
TRANSMISSION CATHODE
186
GATE AND SCAN CONTROL CIRCUITRY
X RAY DETECTOR
184

FIG. 6b

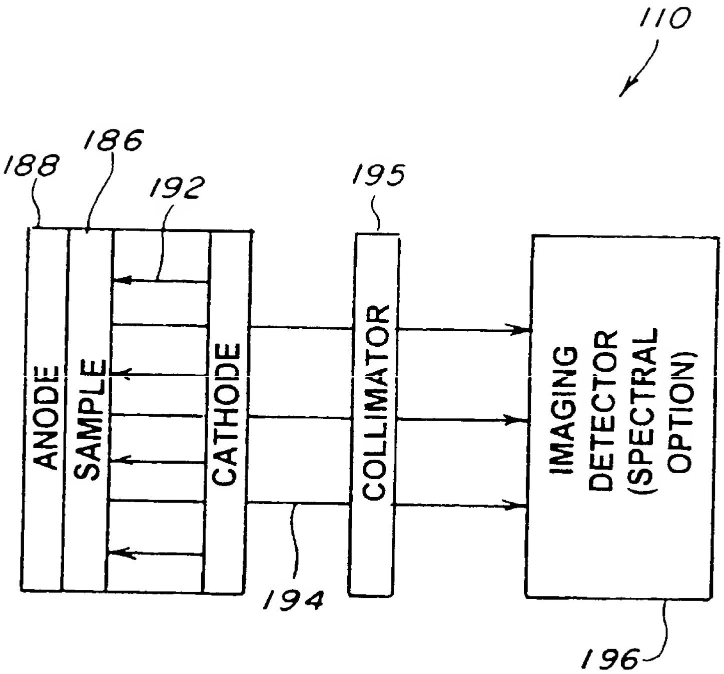

110
188
186
192
195
ANODE
SAMPLE
CATHODE
COLLIMATOR
IMAGING DETECTOR (SPECTRAL OPTION)
194
196

FIG. 6c

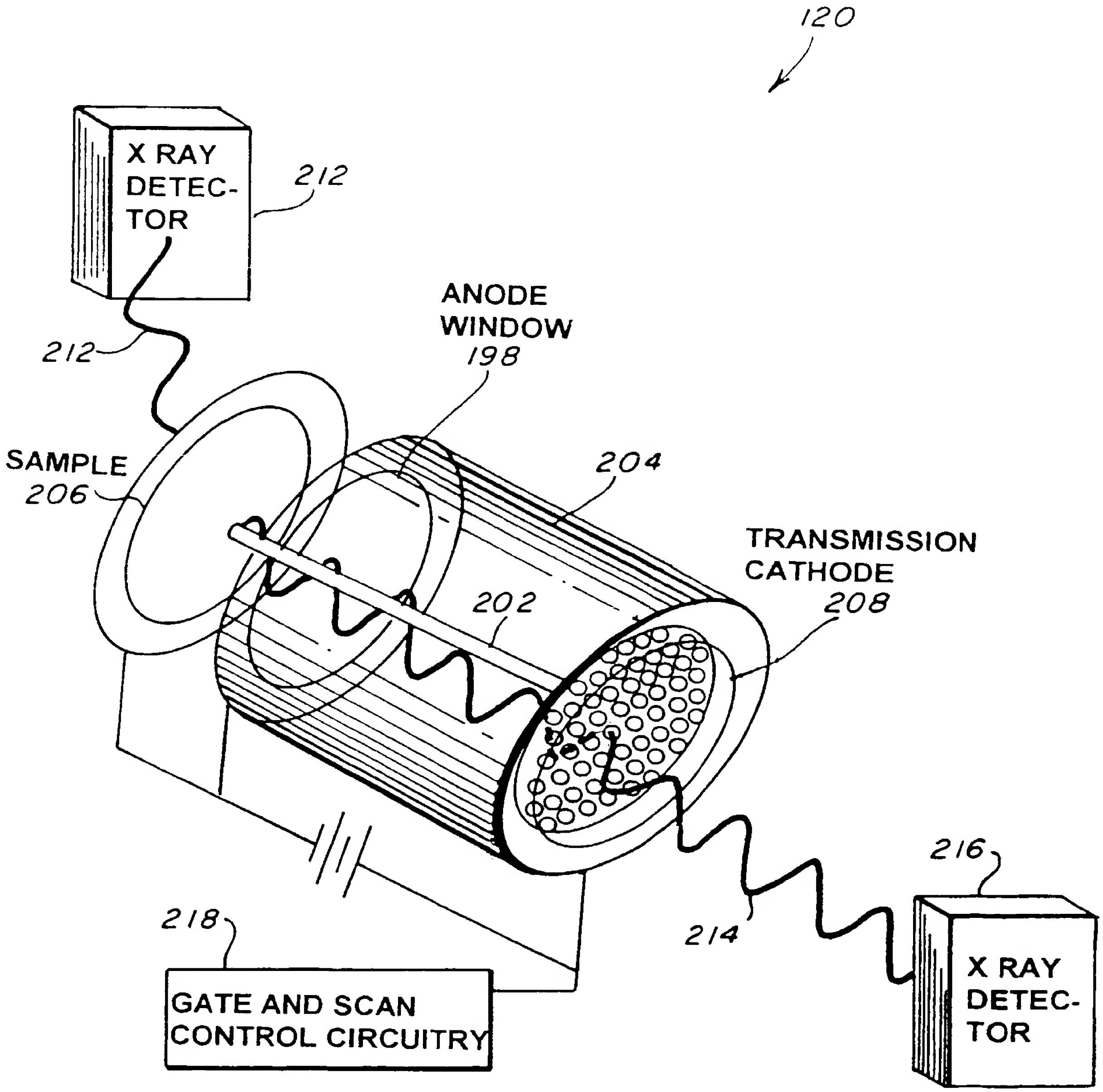

120
X RAY DETEC-TOR
212
212
ANODE WINDOW
198
SAMPLE
206
204
TRANSMISSION CATHODE
208
202
216
218
214
GATE AND SCAN CONTROL CIRCUITRY
X RAY DETEC-TOR

FIG. 6d

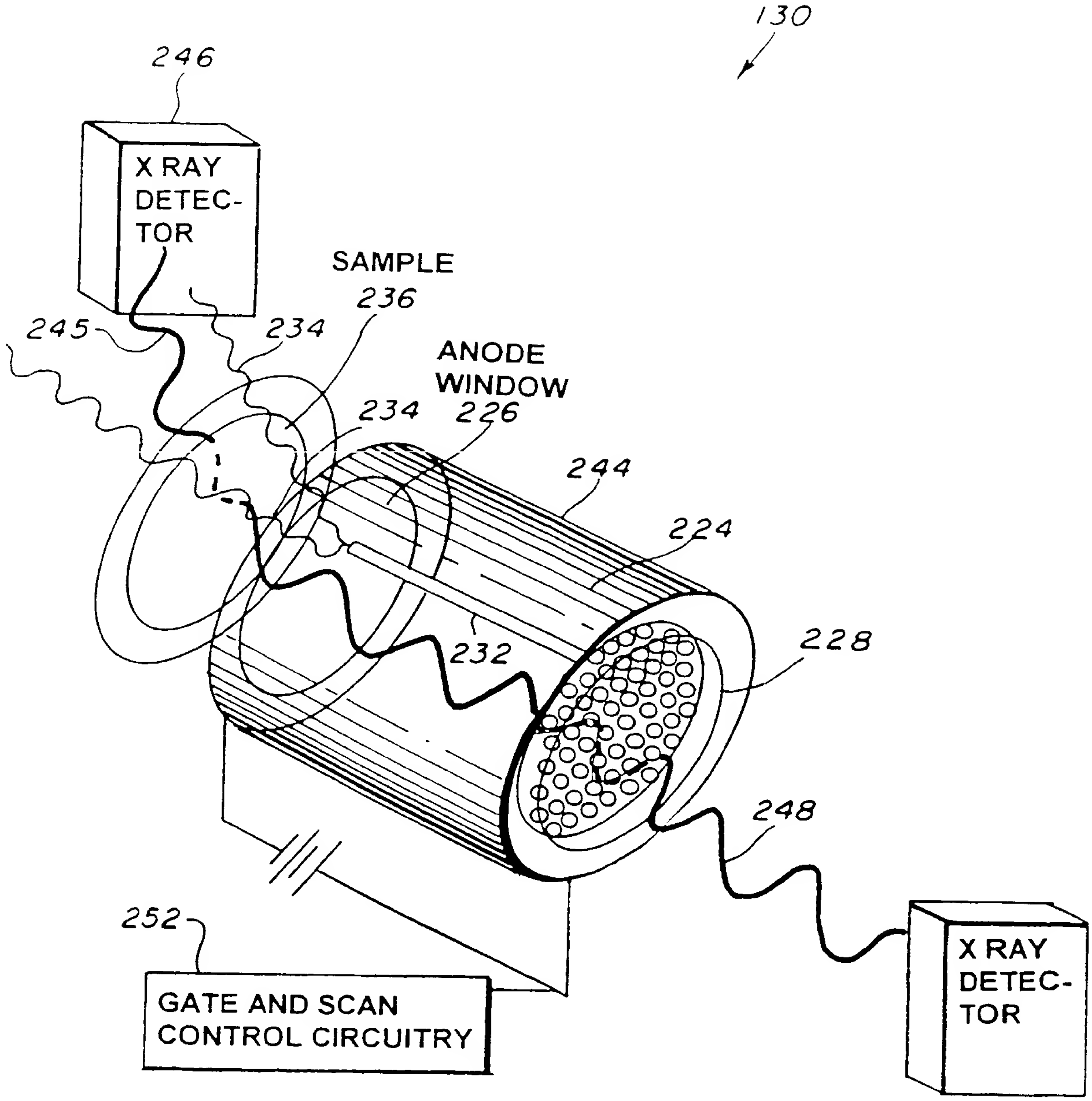

130
246
X RAY DETECTOR
SAMPLE
236
245
234
ANODE WINDOW
234
226
244
224
228
232
248
252
GATE AND SCAN CONTROL CIRCUITRY
X RAY DETECTOR

FIG. 7

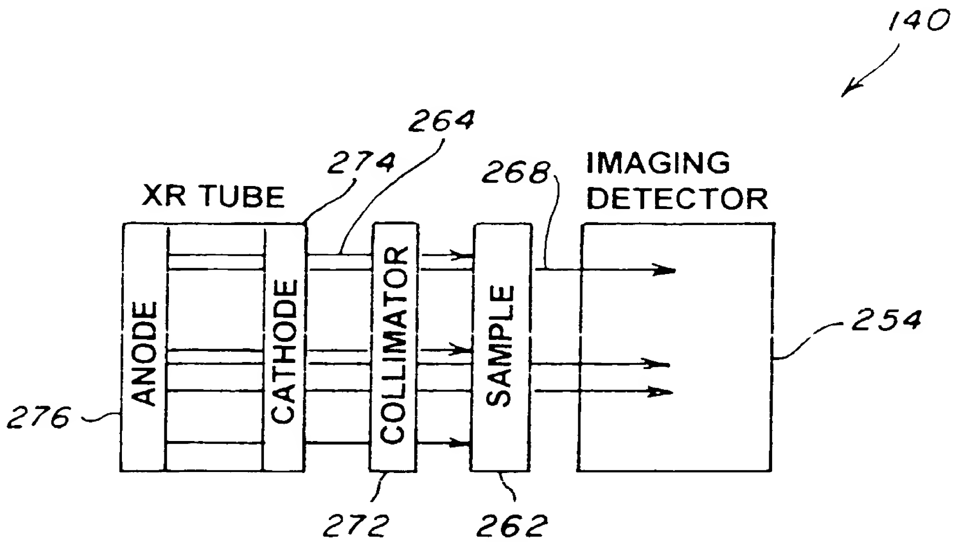

140
264
274
XR TUBE
268
IMAGING
DETECTOR
ANODE
CATHODE
COLLIMATOR
SAMPLE
254
276
272
262

FIG. 8a

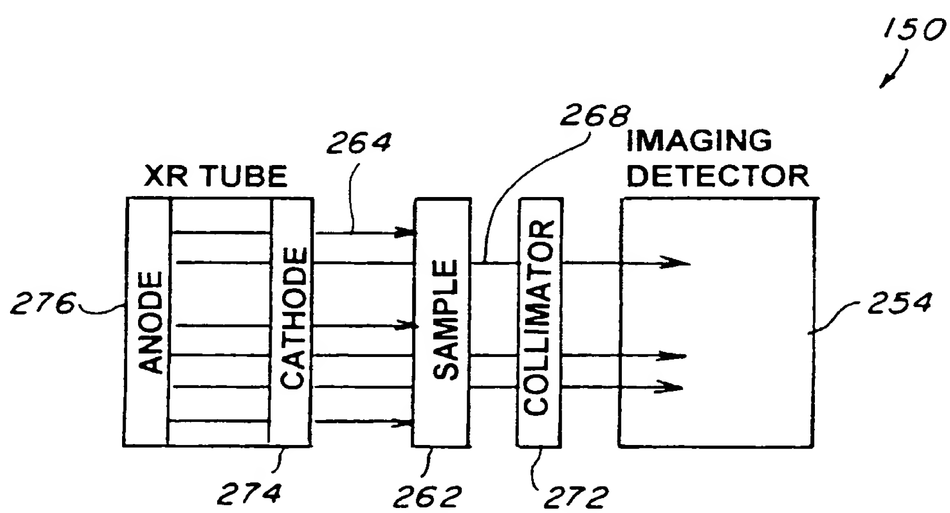

150
268
264
IMAGING
DETECTOR
XR TUBE
276
ANODE
CATHODE
SAMPLE
COLLIMATOR
254
274
262
272

FIG. 8b

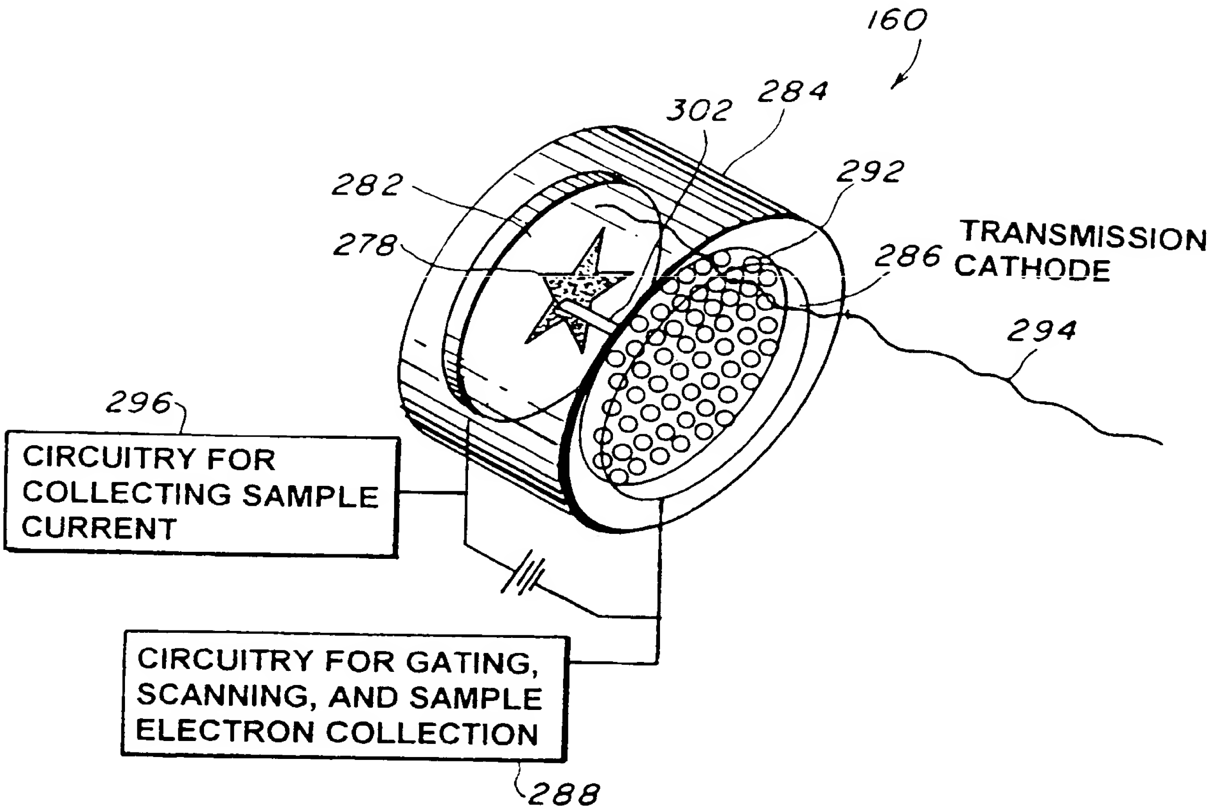

160
302
284
282
292
278
286
TRANSMISSION CATHODE
294
296
CIRCUITRY FOR COLLECTING SAMPLE CURRENT
CIRCUITRY FOR GATING, SCANNING, AND SAMPLE ELECTRON COLLECTION
288

FIG. 9a

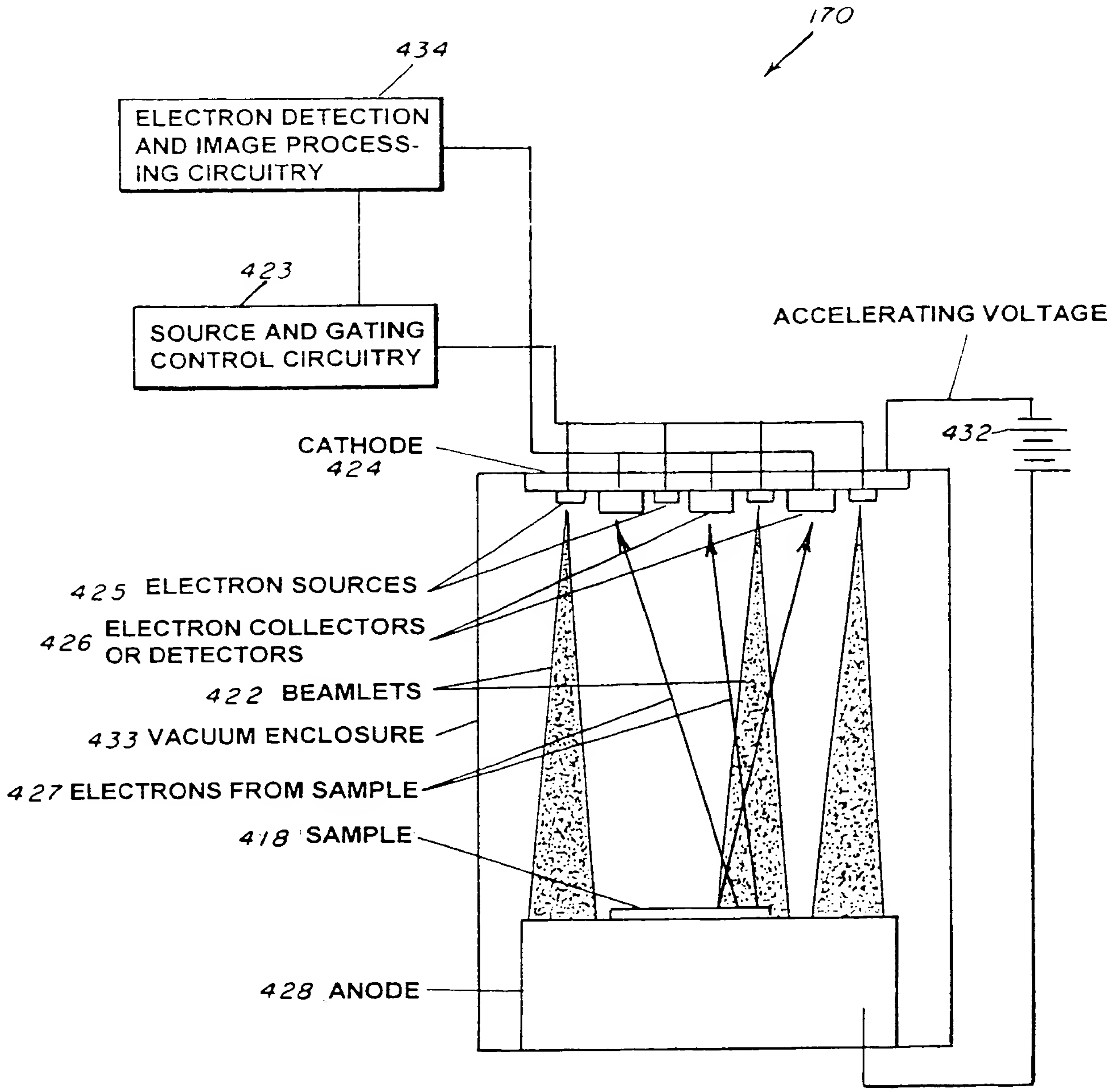

170
434
ELECTRON DETECTION AND IMAGE PROCESSING CIRCUITRY
423
SOURCE AND GATING CONTROL CIRCUITRY
ACCELERATING VOLTAGE
432
CATHODE 424
425 ELECTRON SOURCES
426 ELECTRON COLLECTORS OR DETECTORS
422 BEAMLETS
433 VACUUM ENCLOSURE
427 ELECTRONS FROM SAMPLE
418 SAMPLE
428 ANODE

FIG. 9b

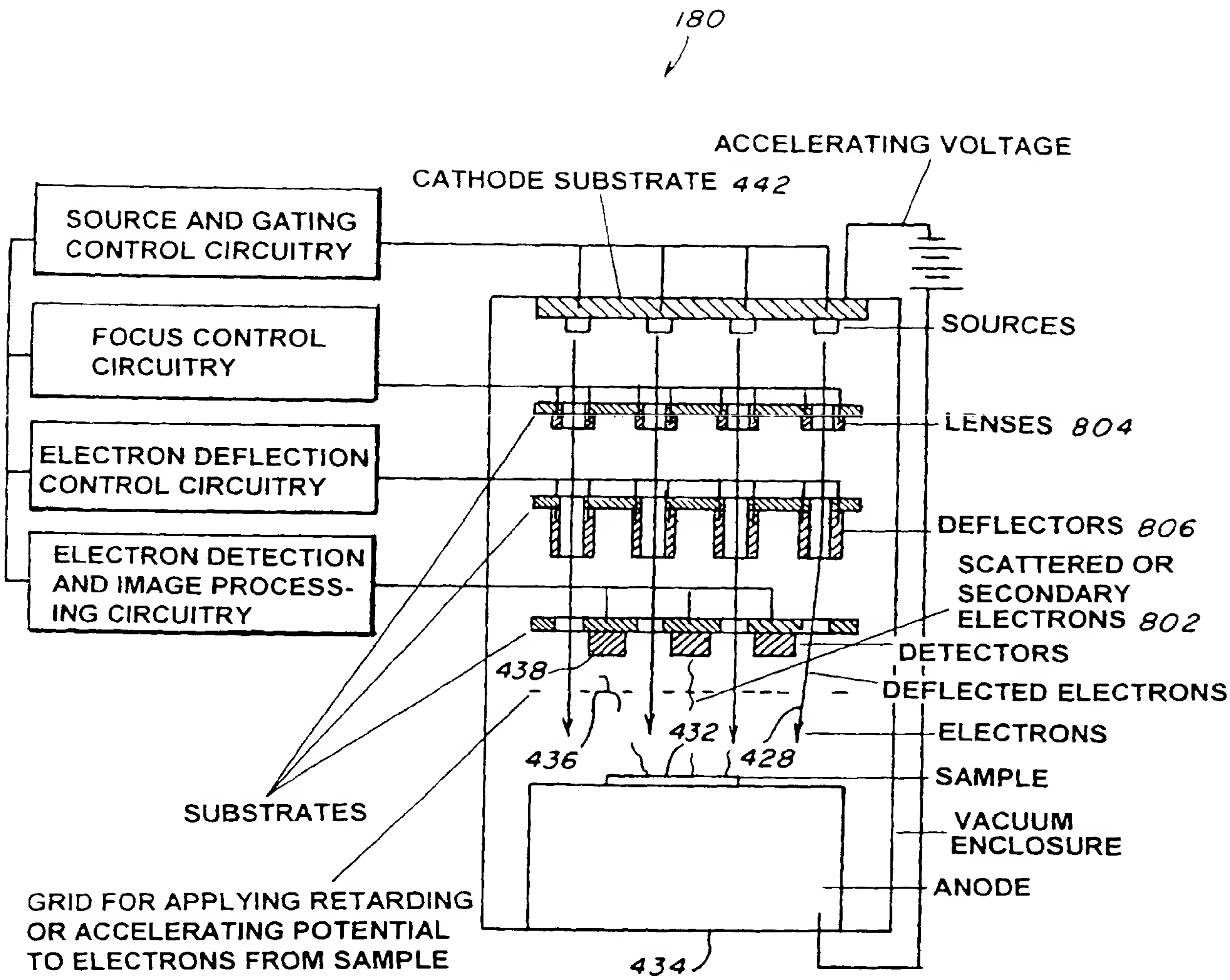

180
ACCELERATING VOLTAGE
CATHODE SUBSTRATE 442
SOURCE AND GATING CONTROL CIRCUITRY
FOCUS CONTROL CIRCUITRY
ELECTRON DEFLECTION CONTROL CIRCUITRY
ELECTRON DETECTION AND IMAGE PROCESSING CIRCUITRY
SOURCES
LENSES 804
DEFLECTORS 806
SCATTERED OR SECONDARY ELECTRONS 802
DETECTORS
DEFLECTED ELECTRONS
ELECTRONS
SAMPLE
VACUUM ENCLOSURE
ANODE
438
436
432
428
434
SUBSTRATES
GRID FOR APPLYING RETARDING OR ACCELERATING POTENTIAL TO ELECTRONS FROM SAMPLE

FIG. 10

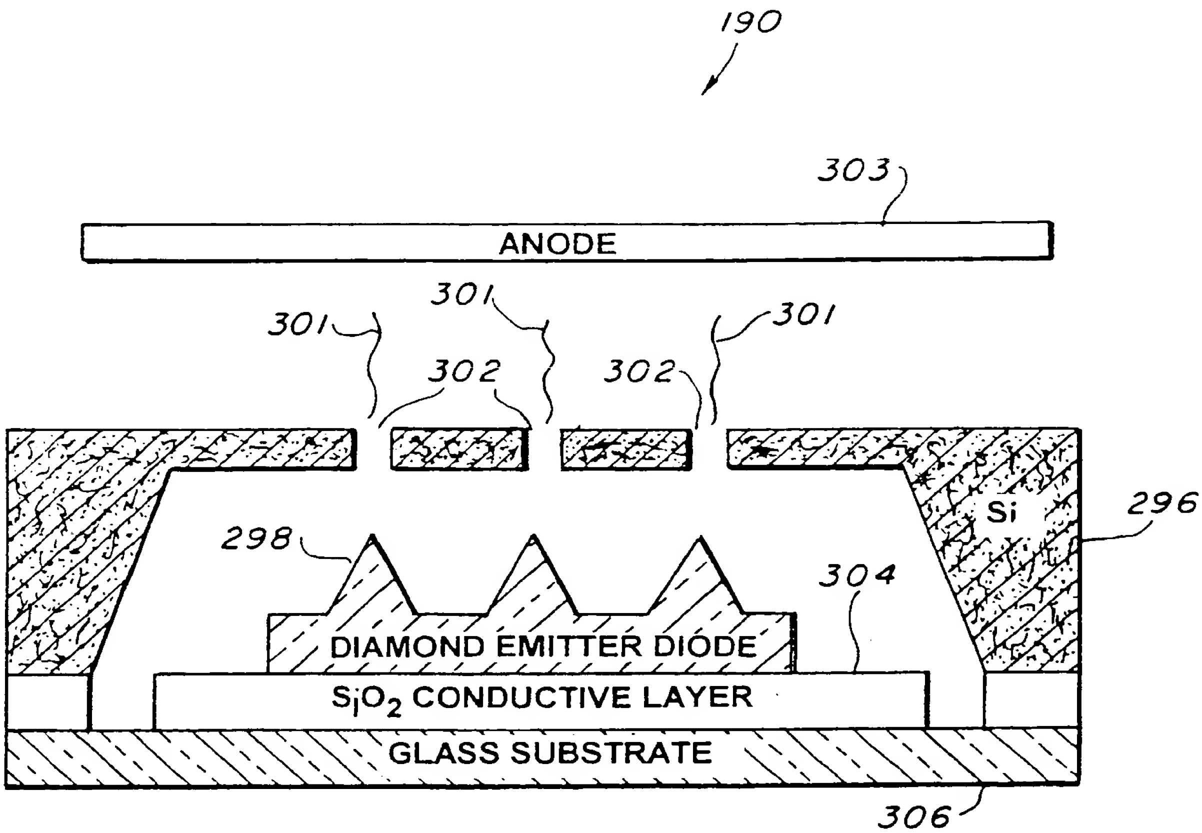

190
303
ANODE
301
301
301
302
302
296
Si
298
304
DIAMOND EMITTER DIODE
SiO2 CONDUCTIVE LAYER
GLASS SUBSTRATE
306

FIG. 11

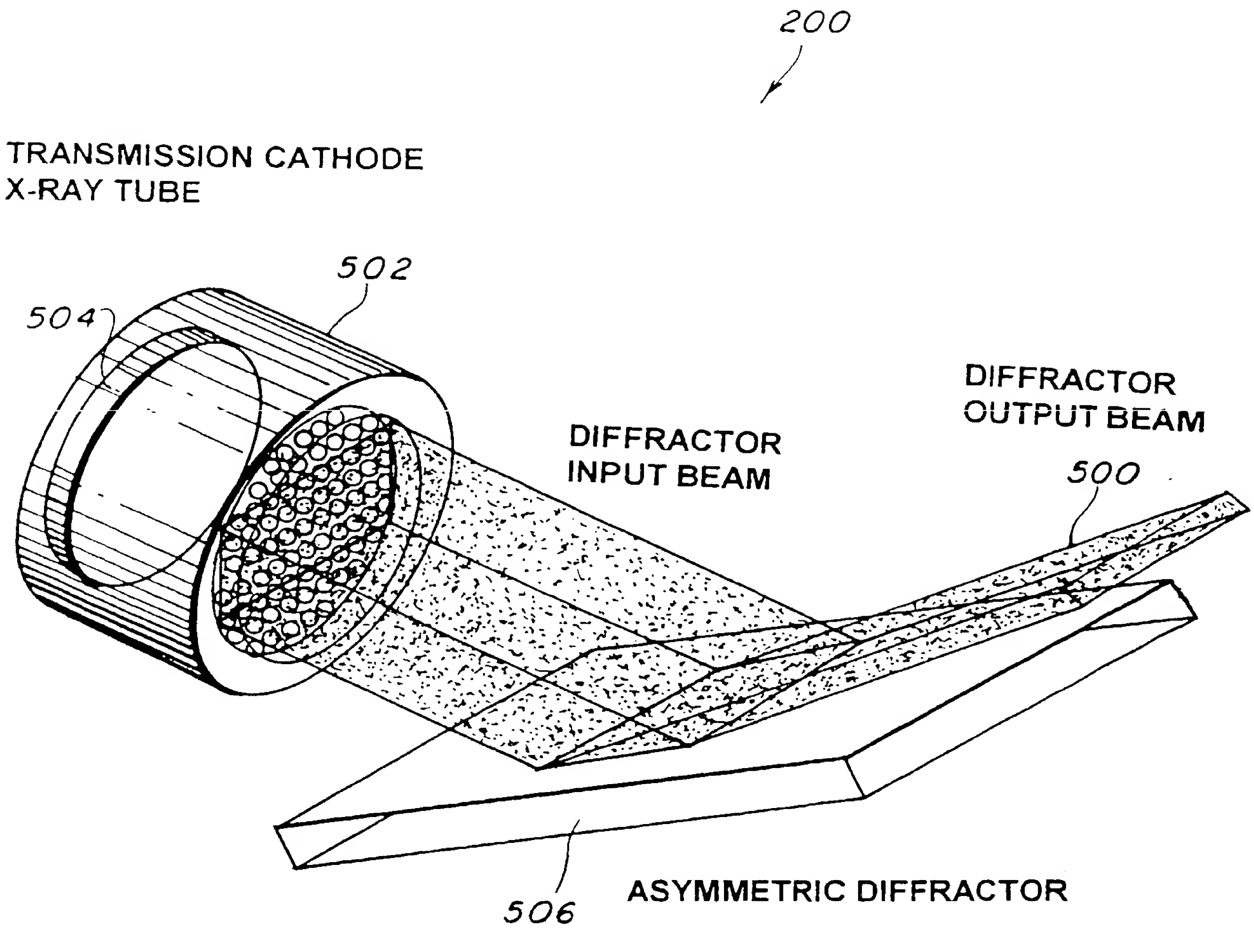

200
TRANSMISSION CATHODE
X-RAY TUBE
502
504
DIFFRACTOR
OUTPUT BEAM
DIFFRACTOR
INPUT BEAM
500
ASYMMETRIC DIFFRACTOR
506

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/14696

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : H01J 9/12
US CL : 378/121, 136; 313/310; 250/310
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 378/44, 119, 121, 122, 136, 137, 140; 313/309, 310, 311; 445/46; 250/310

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST: transmission, cathode, anode, electron, emitter, gating, x-ray tube, scanable, imaging, imager

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A,P	US 6,259,765 B1 (BAPTIST) 10 July 2001 (10.07.2001), all.	1-30, 36 and 37
A	US 4,627,088 A (DOUCET et al.) 02 December 1986 (02.12.1986), all.	1-30, 36 and 37
A	US 5,335,258 A (WHITLOCK) 02 Aug 1994 (02.08 1994), all.	1-30, 36 and 37
A	US 5,717,204 A (MEISBURGER et al.) 10 February 1998 (10.02.1998), all.	31-35
A	US 5,444,242 A (LARSON et al.) 22 August 1995 (22.08.1995), all.	31-35

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 July 2001 (27.07.2001)	04 SEP 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Sharon S. Hoppe Drew A. Dunn Telephone No. 703-308-0956

Form PCT/ISA/210 (second sheet) (July 1998)